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FRAMTIDENS VÄRME OCH KYLA

Final report to the project

Building state-of-the-art supermarket: Putting theory into practice

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Foreword

The authors would like to acknowledge the Swedish Energy Agency for funding this research through the TERMO program. The authors would also like to thank industrial project partners: Advansor AB, Alfa Lu-Ve, Danfoss AB, Green & Cool World Refrigeration, Caverion Sverige AB (formeraly Huurre Sweden AB), ICA Fastigheter AB, Kiona Sweden AB (formerly IWMAC Operation Center AB), and Svensk Energi & Kylanalys AB.

The authors would like also to thank the undergraduate students who did their work on certain tasks in the project as part of their master thesis or course work.

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Summary

Supermarkets are energy intensive buildings where our documented studies show that CO2 integrated refrigeration system offers at least 15% annual energy savings compared to standard CO2 system and at least 25% compared to conventional systems with HFC's.

This project applied the knowledge accumulated through the research in supermarket energy systems by building a unique case study, where today's most efficient, environmentally friendly and cost-effective features of an energy system for supermarkets were implemented. A highly efficient supermarket was designed, installed, monitored, thoroughly evaluated, and well documented.

This report includes summary of the key findings from the different research activities in the project, which focused on designing and evaluating the performance of the reference case study of a highly efficient energy system for supermarkets in Sweden. The proposed energy system solution, which is based on earlier research studies, has been defined. Followed by presenting the details of the selected case study, which is a supermarket in Bålsta.

The key findings from this project have been presented in different categories representing the key features of the proposed system solution. Performance analysis of the energy system to cover the refrigeration, air conditioning, and heating demand has been presented in separate section for each thermal demand, where the effect of the installed geothermal loop has also been included. The analysis results of the overfeeding function of the evaporators have been presented in a dedicated section.

The overall energy use of the supermarket building has been studied and the system was benchmarked against data from number of old and new supermarkets in Sweden. Two specialized computational tools for simulating energy use in supermarket buildings have been used to estimate thermal demands and the energy use in the case study, the models were validated against field measurement data.

Investigation results of two additional supermarkets are also included in the report. The supermarkets have been defined as supporting case studies with common features to the reference case study of Bålsta supermarket. The supporting case studies also had some other interesting features that were not possible to implement in Bålsta supermarket.

Sammanfattning

Livsmedelsbutiker är energiintensiva byggnader där våra dokumenterade studier visar att CO2-integrerat kylsystem ger minst 15 % årliga energibesparingar jämfört med standard CO2-system och minst 25 % jämfört med konventionella system med HFC.

Detta projekt tillämpade den kunskap som samlats genom forskningen i stormarknaders energisystem genom att bygga en unik fallstudie, där dagens mest effektiva, miljövänliga och kostnadseffektiva funktioner i ett energisystem för stormarknader implementerades. En mycket effektiv livsmedelsbutik designades, installerades, övervakades, utvärderades grundligt och dokumenterades väl.

Denna rapport innehåller en sammanfattning av de viktigaste resultaten från de olika forskningsaktiviteterna i projektet, som fokuserade på att designa och utvärdera prestandan för referensfallstudien av ett högeffektivt energisystem för stormarknader i Sverige. Den föreslagna energisystemlösningen, som bygger på tidigare forskningsstudier, har definierats. Därefter presenteras detaljerna i den valda fallstudien, som är en stormarknad i Bålsta.

De viktigaste resultaten från detta projekt har presenterats i olika kategorier som representerar nyckelfunktionerna i den föreslagna systemlösningen. Prestandaanalys av energisystemet för att täcka kyl-, luftkonditionerings- och värmebehovet har presenterats i separata avsnitt för varje termiskt behov, där effekten av den installerade geotermiska slingan också har inkluderats. Analysresultaten av förångarnas övermatningsfunktion har presenterats i ett särskilt avsnitt.

Livsmedelsbutiksbyggnadens totala energianvändning har studerats och systemet jämfördes med data från antal gamla och nya stormarknader i Sverige. Två specialiserade beräkningsverktyg för att simulera energianvändning i stormarknadsbyggnader har använts för att uppskatta värmebehov och energianvändning i fallstudien, modellerna validerades mot fältmätningsdata.

Undersökningsresultat från ytterligare två stormarknader ingår också i rapporten. Livsmedelsbutikerna har definierats som stödjande fallstudier med gemensamma drag för referensfallstudien av Bålsta stormarknad. De stödjande fallstudierna hade också en del andra intressanta egenskaper som inte var möjliga att implementera i Bålsta stormarknad.

1. Introduction

Supermarkets are the highest energy intensive commercial buildings consuming almost double the office building. They are responsible for consuming about 3-4% of the total annual electricity in industrialized countries and are the largest consumers in Europe of high GWP refrigerants; about 30% of Europe's HFC consumption [1]. Therefore, the need is great for environmentally friendly and energy efficient systems for supermarkets.

Supermarket refrigeration systems working with Carbon dioxide (CO2) as a refrigerant have been widely applied in northern Europe especially in Scandinavian countries. The most advanced CO2 refrigeration system, referred to as state-of-the-art system, is a single integrated system providing all refrigeration, heating and air conditioning needs with quite high efficiencies and competitive installation cost. This system has been defined and studied in the Effsys EXPAND project, P04: "The energy efficient supermarket of tomorrow".

The results from the Effsys EXPAND project P04 are published in doctoral thesis [1], and can be summarized in the following. The state-of-the-art system is expected to offer at least 15% annual energy savings compared to standard CO2 system and at least 25% compared to conventional systems with HFC's; making the system the most efficient that can be installed today in Sweden. An average size supermarket in Sweden is expected to consume about 500MWh electricity for refrigeration, heating and air conditioning, which means that the state-of-the-art system will result in savings of at least 75 to 100MWh/year/system. The energy savings are especially important since the EU F-gas regulations means that the installation of CO2 based refrigeration systems for supermarkets will further accelerate due to the ban on installing systems with HFC's.

The state-of-the-art system solution has been extensively studied theoretically and some of its key features have been evaluated individually in field measurements. However, the system as a whole with all its design features, monitoring, and control has not been built yet. This project included finding, with the help of the industrial partners, a case study of a supermarket where the researchers at KTH had unique opportunity to be involved in the system design, specifying needed instrumentations, identifying the data logging requirements, having access to data from all energy sub-systems in the supermarket, defining the control strategies, and thereafter, comprehensively evaluated the system performance.

This project facilitated transferring research findings into common practice and gives first hand feedback to researchers and involved partners on the unforeseen practical obstacles for the full implementation of the suggested system concept.

All physical and design details of this supermarket are well-documented and made available to the public through the project publications. The evaluation method and how the performance figures were produced are also documented in the publications. The system in this study will be a reference case study for future installations in Sweden.

1.1. Background:

The research work on supermarket energy systems at the Energy Technology Department at KTH extends back to about two decades. The research has been conducted by computer modelling, experimental investigations, and field measurements in seven main projects funded by the Swedish Energy Agency. Three PhD theses have been published in this area by the Energy Technology department at KTH: "Energy Use in Supermarkets" by Jaime Arias in 2005, "Carbon Dioxide in Supermarket Refrigeration" by Samer Sawalha in 2008, and "State-of-the-art Integrated Refrigeration Systems in Supermarkets" by Mazyar Karampout in 2021.

The early research work at the Energy Technology department at KTH studied several possible features to improve the efficiency of CO2 refrigeration system for supermarkets, where the most efficient and cost-effective features have been used in the proposal of state-of-the-art system solution. The proposed system has the following key features:

- Two-stage heat recovery providing all space and tap water heating demands in the supermarket
- Providing all air conditioning demand
- Flash gas by-pass with parallel compression
- Increased medium and low-level evaporation temperatures by flooding the evaporators using, for example, an ejector
- Geothermally connected

The state-of-the-art system has been studied mainly theoretically where some features, such as heat recovery and air conditioning, have been compared to field measurements. Our experience from working with field measurements analysis in the past 15 years shows that supermarket energy systems are instrumented with quite large number of sensors; however, the following common issues with field measurements makes the systems analysis very difficult or almost impossible:

- Missing key measuring points, for example, temperatures, separate electric power meters, number of compressors running, etc.
- Data is not synchronized which requires time consuming data processing and filtering
- Usually, we access data from refrigeration system but have no access to other energy systems; such as space heating and air conditioning. This is mainly due to different responsible companies and providers of monitoring systems.
- Missing information about the buildings, for example, sales and total areas, height, number and size of offices and other rooms, etc.
- Lack of information on the logic of system control

To overcome the listed challenges important assumptions, extensive data processing and different levels of verifications had to be done. Therefore, in this project the researchers have been involved in the very start of the project to define the needed measurements and suggest how the system should be monitored, and the data is collected.

The state-of-the-art energy system for supermarkets did not exist in real installation at the project start. Some installed systems may have some common features with the state-of-the-art system, but they are not necessarily optimized in design and cost. This project offered a rare opportunity where researchers at KTH were involved at early stage of designing the state-of-the-art system and gathered all needed information on the case study. The researchers made sure that the system is instrumented, monitored and evaluated as if it would have been a test rig running in our laboratory. The case study system included:

- Measurement of all energy demands in the supermarket: medium temperature refrigeration, low temperature refrigeration, space heating, domestic hot water, air conditioning, lighting, etc.
- Energy analysis at different levels: Detailed sub-systems and the overall system.
- Compare and validate calculation tools for energy use in supermarkets, mainly:
  - Our in-house built codes that model the state-of-the-art energy system
  - Available tools to calculate building energy demands; eg. CyberMart tool and EnergyPlus.
- Detailed performance analysis of components; such as, compressors, gas coolers, cabinets, etc
- Detailed feedback to stakeholders in every aspect relate to energy, for example, design capacities vs actual demand, efficiencies, control, etc.
- Provide unique reference case in the field which offers the key following points:
  - Detailed information about building dimensions, layout, type of windows and walls, orientation, etc.
  - Load profiles and activity schedules
  - Measured temperatures in the different building zones
  - Accurate energy use, efficiency, and energy intensity figures

The work in this project provides solid field measurement analysis based on high quality data and validated calculation tools.

1.2. Objectives

The main objective of this project is to apply the knowledge accumulated through the research in supermarket energy systems by building a unique demonstration case study where today's most efficient, environmentally friendly and cost-effective supermarket will be designed, installed, monitored, thoroughly evaluated, and well documented.

The project aims at achieving the following goals:

- A new supermarket built that has at least 15% less annual energy use compared to standard CO2 system and at least 25% less compared to conventional systems with HFC's.
- The supermarket's energy system has full instrumentation in all energy sub-systems and close monitoring, as if it is a test rig running in a laboratory.

- Thoroughly evaluated supermarket energy system through modelling and well instrumented field measurement.
- Modelling and analysis tools/methods for supermarket energy systems that are well verified.
- Transfer of research findings into future common practice.
- Unique reference case at national and international levels.
- Proposal for the next generation of state-of-the-art energy system for supermarkets

1.3. Methodology and implementation

The investigations in this project have been based on computer simulation modelling and analysis of field measurements from selected case studies. In parallel, extensive literature review has been continuously conducted and updated, which can be clearly seen in the project publications.

The consortium in this project includes industrial partners having competence and access to resources that are keys to the project implementation and success. The industrial partners representing different stakeholders in the field, such as: supermarket buildings owners, energy systems installers, component providers, companies providing monitoring and data acquisition systems, and consultants.

Together with the industrial partner a case study was selected where the researchers at KTH had the opportunity to be involved in the system design, specifying needed instrumentations, identifying the data logging requirements, having access to data from all energy sub-systems in the supermarket, defining the control strategies, and thereafter, comprehensively evaluate the system performance.

Theoretical modelling combined with field measurements analysis from selected case studies have been conducted to design and build the most efficient energy system for supermarkets in Sweden with the available technologies at the design phase of the project. Comprehensive analysis has been conducted to the reference case study, and to two additional supporting case studies, selected as good examples.

The researchers in this project have been the PhD student Sotirios Thanasoulas, the project leader and principal supervisor Associate Professor Samer Sawalha, and the co-supervisor Associate Professor Jaime Arias. All have been employed at the Energy Technology department during the project implementation.

Several master thesis students participated in field measurement analysis and the computer modelling. The published master thesis reports produced by the students are open for access through the KTH library and included in the publication list in this report.

2. Results

The key findings from this project are presented in the following sections, where each section includes research block in the project. The relevant publications to each research block are listed at the end of each section, where more results and details of the research work can be found.

2.1. The reference energy system solution

The investigated system solution in this project is based on earlier research work that has been published in the doctoral thesis of Mazyar Karampour [1], where an efficient integrated energy system solution for supermarkets in Sweden was proposed. The proposed system uses CO2 as refrigerant and had several features for efficiency increase, such as: flooding (or overfeeding) the evaporators, use of parallel compression, recovering heat, and implementing geothermal integration, schematic of the system is presented in Figure 1. The centralized integrated system solution can cover all the refrigeration, space heating, domestic hot water, and air conditioning demands in the supermarket building.

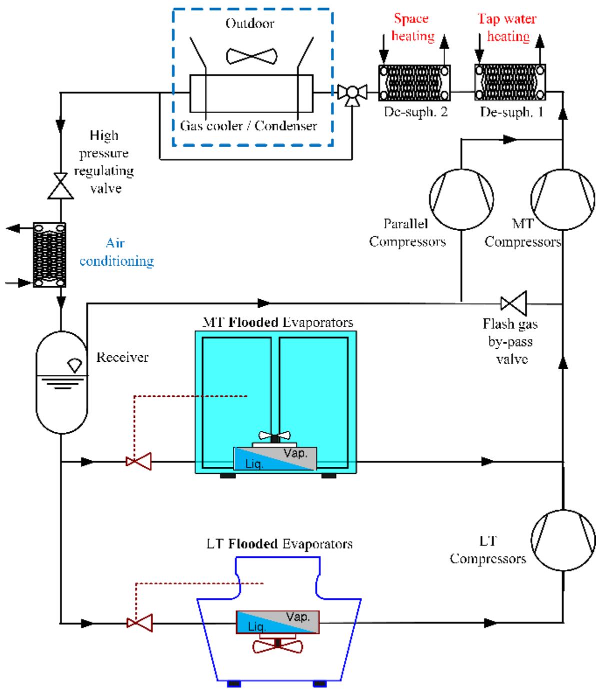
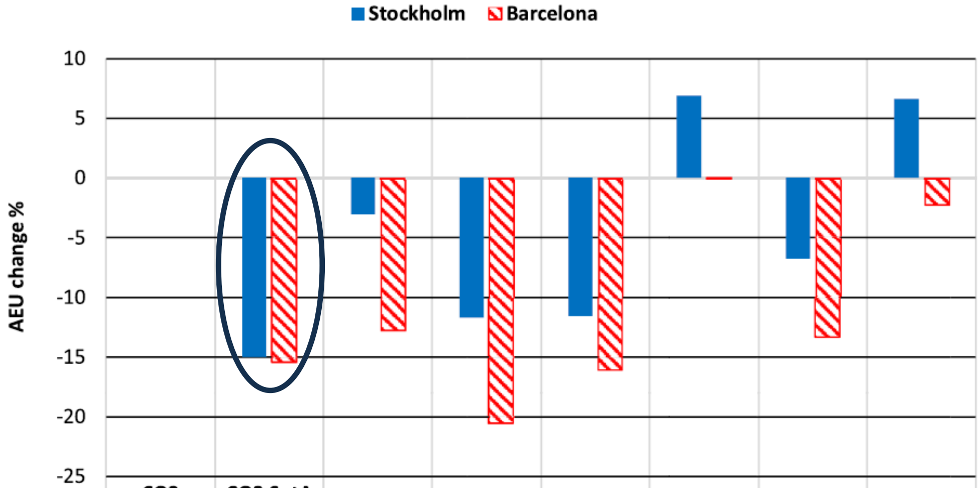


Figure 1: Schematic diagrams of the proposed integrated

The expected energy savings from implementing each of the features of the proposed system was analysed and quantified. For example, flooding the evaporators and using parallel compression is expected to save about 15% of the energy use compared to a standard CO2 system in Stockholm, as can be observed in Figure 2. The figure also presents comparison to other possible system solutions, which shows that the proposed system solution is the most efficient alternative for the outdoor temperatures of Stockholm.



	CO2 standard booster (ref.)	CO2 SotA (PC+flooded MT&LT)	Cascade R290-CO2	Cascade NH3-CO2	R404A DX	R404A Indirect	R449A DX	R449A Indirect
Stockholm	0.0	-15.0	-3.1	-11.7	-11.6	6.9	-6.8	6.6
Barcelona	0.0	-15.4	-12.8	-20.6	-16.2	0.0	-13.3	-2.3

Figure 2: Impacts of modifications on annual energy use (AEU) compared to a standard CO_2 system and other potential energy system solutions.

A typical energy system in supermarkets provides air conditioning needs using standalone systems; however, in the proposed integrated system solution, air conditioning is provided by the centralized system. Air conditioning needs are provided with competitive efficiency to conventional air conditioning systems with the HFC refrigerant R410A. Seasonal Energy Efficiency Ratio (SEER) of the proposed system compared to a conventional R410 standalone system are presented in Figure 3.

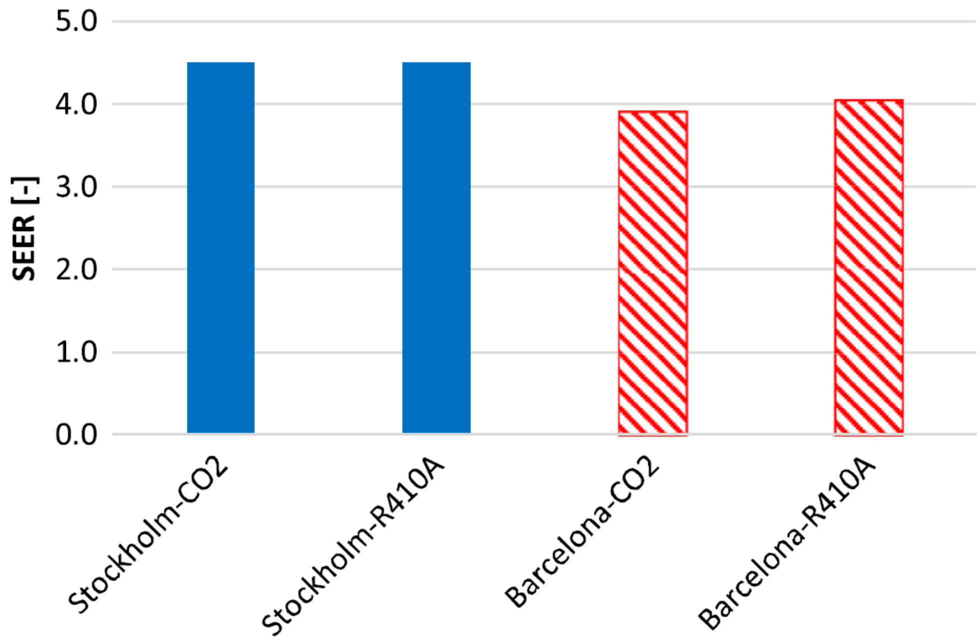


Figure 3: Seasonal Energy Efficiency Ratio (SEER) for air conditioning by CO2 integrated system and by a standalone R410A system in Stockholm and Barcelona.

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Another important feature of the proposed system solution is the efficient heat recovery, where the cost for heating can be reduced compared to using other heating alternatives, such as district heating or an air source heat pump (ASHP), as can be seen in Figure 4.

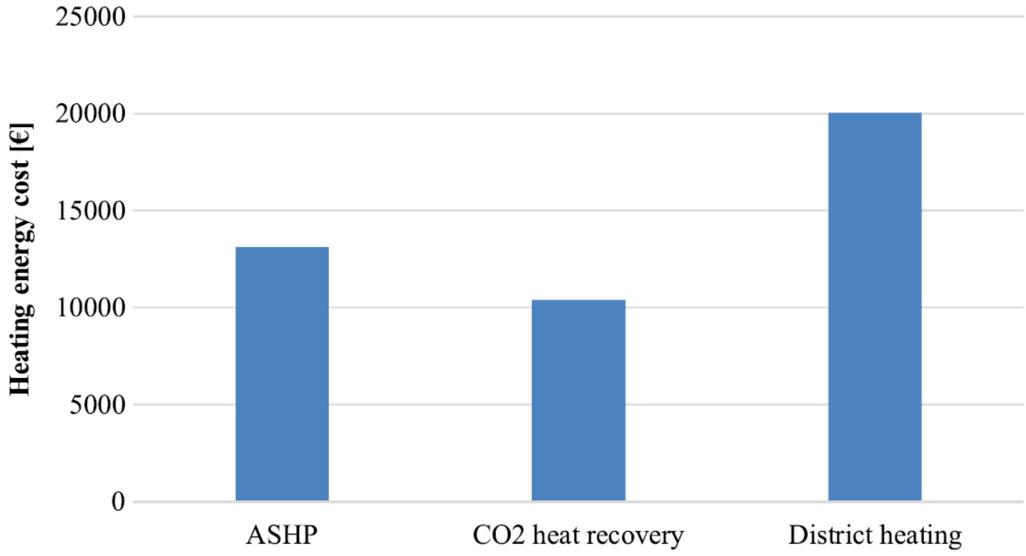

Figure 4: Annual heating energy cost of using air source heat pump (ASHP), CO2 heat recovery, and district heating [euros].

In addition to the significant energy savings the proposed system solution offers, it uses the natural refrigerant CO2 which does not have unforeseen threats to the environment and safe to be used in distribution lines in the supermarket's sales areas.

The theoretical analysis of the proposed system solution has been used as the basis for designing, building, and analysing the system in this research project.

Relevant publication/s:

Karampour, M., 2021. State-of-the-art Integrated Refrigeration Systems in Supermarkets: An Energy Efficiency Evaluation Based on Field Measurements Analysis and Computer Simulations, Doctoral thesis, Energy Technology department, KTH.

2.2. The case study-Bålsta supermarket

In cooperation with the project partners, the case study has been identified and selected, which is an ICA MAXI supermarket, it can also be categorized as a hypermarket because the sales area is larger the 2500m^2. However, we refer in this report to all retail store categories such as supermarkets.

The case study supermarket is in Bålsta, which is about 45 km northwest of Stockholm. The supermarket has a total area of 6780 m^2, among which the sales area is about 4500 m^2. The supermarket building includes a pharmacy, a café with Pizza service, and a post office area. It has been in operation since January 2021. Satellite picture of the supermarket and a layout of the area use are presented in Figure 5.

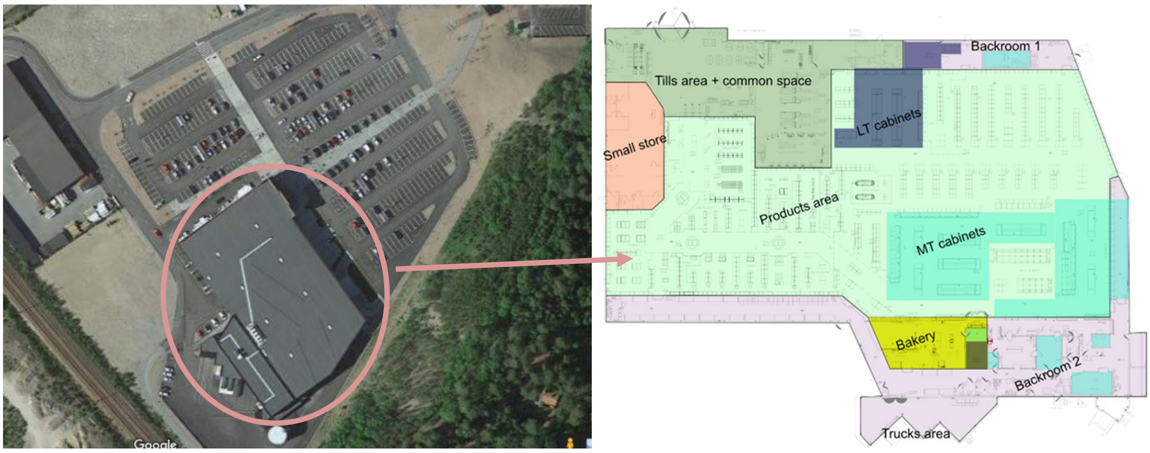

Figure 5: Satellite picture of the supermarket building and layout showing the area use.

The supermarket has medium temperature (MT) cabinets with total length of 240 m and low temperature (LT) cabinets of 58m. The installed capacity at the medium temperature level is 113kW, where 65kW of the capacity is in the cabinets and 48kW is in the cold rooms. At the low temperature level, the installed capacity is 15,5kW in the cabinets (freezers), and 22kW is in the freezer rooms, totaling 37,5kW.

The energy system is designed and built to provide all the supermarket's refrigeration, heating, and air conditioning demands in a centralized (all-in-one) energy system solution, which is sometimes referred to as an integrated system in this report. The core of the energy system is a CO2 booster refrigeration system which covers the air conditioning demands and recovers the space heating and domestic hot water needs in the supermarket building. Figure 6 is a schematic diagram showing the refrigeration system and how it is integrated into the HVAC system.

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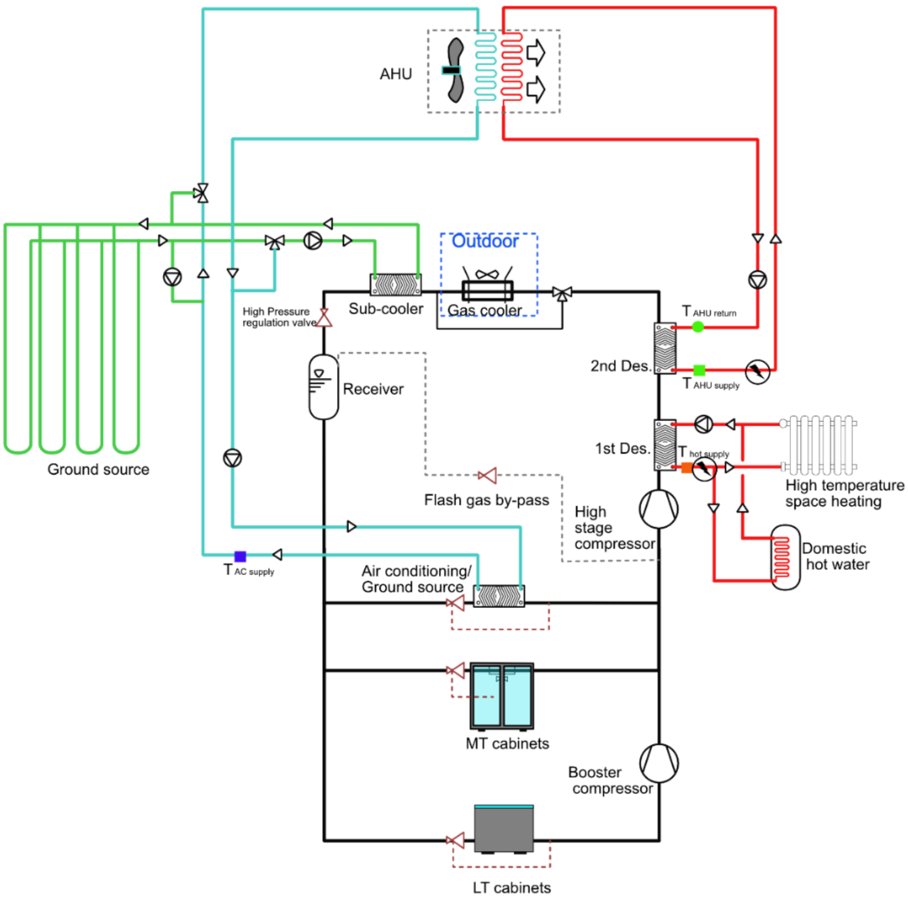

Figure 6: Schematic diagram of the integrated energy system convering refrigeraiton, heating, and AC demands.

As can be seen in the schematic in Figure 6, heat is recovered in two heat exchangers, de-superheaters, in series at the discharge line of the high stage compressors. This facilitates efficient utilization of the temperature glide of CO2 in the de-superheaters by recovering high temperature thermal demands, such as DHW and radiators space heating, in the 1st de-superheater, while low temperature space heating demands are provided by the 2nd de-superheater.

When recovering heat from a refrigeration system, the capacity for heat recovery is limited by the refrigeration demand. In a cold winter day, the refrigeration demand is typically low, and the heating demand is high. Therefore, the integrated energy system, presented in Figure 6, is connected to six boreholes of 200m depth each, where the ground is used as an additional heat source in the winter to increase the heating capacity of the system.

The heat is extracted from the ground in the winter via the heat exchanger denoted as “air conditioning/ground source” in the schematic in Figure 6. During the summer operation, the ground loop is disconnected from this heat exchange and the heat exchanger is used to provide space cooling in connection to the air handling unit (AHU). The ground is used as a heat sink during summer operation providing free sub-cooling to the refrigeration system, hence, increasing its efficiency.

The refrigeration system is equipped with liquid ejector overfeeding of the medium temperature evaporators, this will eliminate internal superheating and allow the system to run at higher evaporation temperature. The liquid ejector connection is not included in the schematic in Figure 6 for the sake of simplicity, however, the concept of liquid ejector overfeeding is presented in Figure 7.

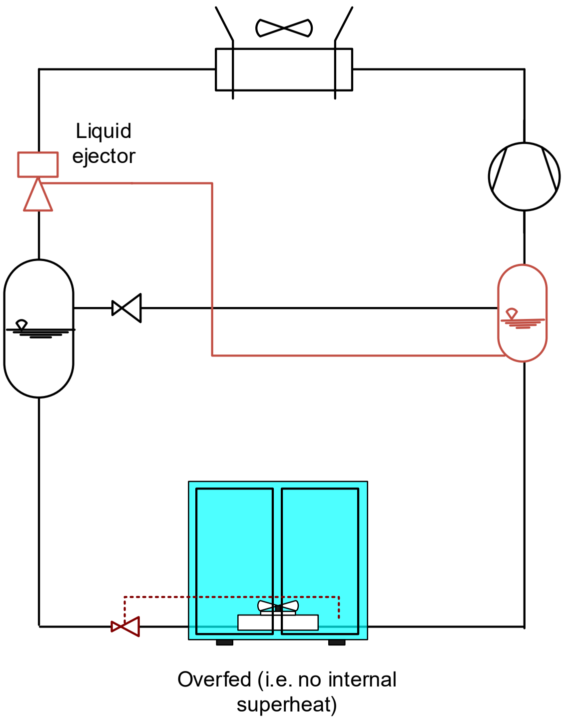

Figure 7: Schematic diagram of the liquid ejector overfeeding concept

To run comprehensive evaluation of the energy system performance, detailed measurements have been installed in the system, continuously logging the temperature values before and after each system component and the pressure at each pressure level in the refrigeration system. Electric power consumption of the key components of the refrigeration system and the sub energy systems in the supermarket's energy system have been measured. The categories of the electric power meters are shown in Figure 8.

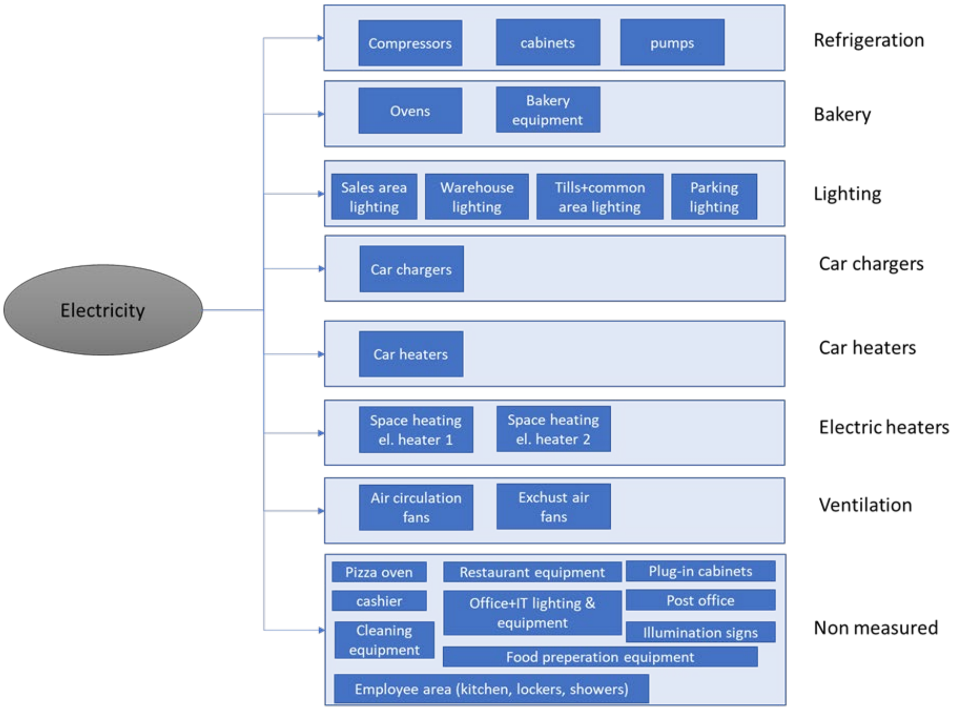

Figure 8: Map of electric power meters

It can be observed in Figure 8 that there is a group of energy users/activities that were not measured separately. Therefore, estimations of electricity consumption were made based on available information from manufactures datasheets, when applicable or possible.

The system has been monitored and the data has been collected since the start of the operation in January 2021. The energy performance analysis has been performed for at least two years of operation.

The different functions of the energy system have been studied separately to evaluate the performance of the system in comparison to other typical standalone solutions. In the following sections, the energy performance of the system to cover the refrigeration, heating, and air conditioning demands is presented and analysed.

Relevant publication/s:

- S. Thanasoulas, J. Arias och S. Sawalha, ”Theoretical analysis of the power and annual energy demands of a supermarket with a CO2 refrigeration cycle,” i 14th Gustav Lorentzen Conference, Kyoto, Japan, 2020.
- S. Thanasoulas, J. Airas och S. Sawalha, ”Supermarket case study: analysis of refrigeration system with heating, air conditioning and ground storage integration,” i 26th International Congress of Refrigeration, Paris, France, 2023.

2.3. Refrigeration performance

The detailed measurements in the system allowed for comprehensive analysis of the thermal demands and energy use in the system. Figure 9 shows the average daily thermal demands and energy use in the main parts of the system at daily average outdoor temperatures over a period of one year. Negative values of energy in the figure are for

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cooling demand or electric energy use, while positive values are for heating demand or heat rejection from the system.

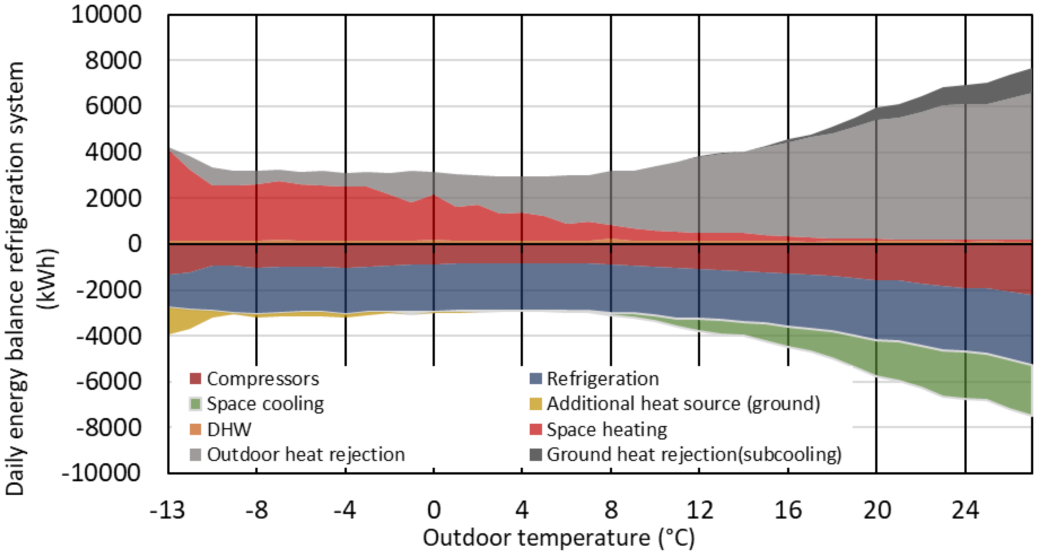

Figure 9: Average daily thermal demands and energy use versus daily average outdoor temperature.

It can be observed in the results presented in Figure 9 that the DHW demand is very small in the system, almost negligible. The function of the geothermal system can also be observed, where at low outdoor temperature heat is extracted from the ground to help the system covering the rising space heating demand. However, at high outdoor temperature, part of the heat is rejected into the ground via the sub-cooler to improve the systems efficiency.

The plot in Figure 9 gives important insight into the control of the condenser/gas cooler. At outdoor temperatures higher than 12°C, the heating demand is low and most of the heat is rejected to the ambient via the condenser/gas cooler. At lower outdoor temperatures than 12°C, heating demand increases, and the system operates at heat recovery mode rejecting less heat via the condenser/gas cooler. At the lowest recorded temperature of -13°C, the condenser is by-passed and all the available heat is recovered to heat up the supermarket's building.

The main thermal demands in the system are medium temperature (MT) and low temperature (LT) refrigeration, space heating, and air conditioning. The demands, in thermal power, are plotted versus the outdoor temperature for a period of one year.

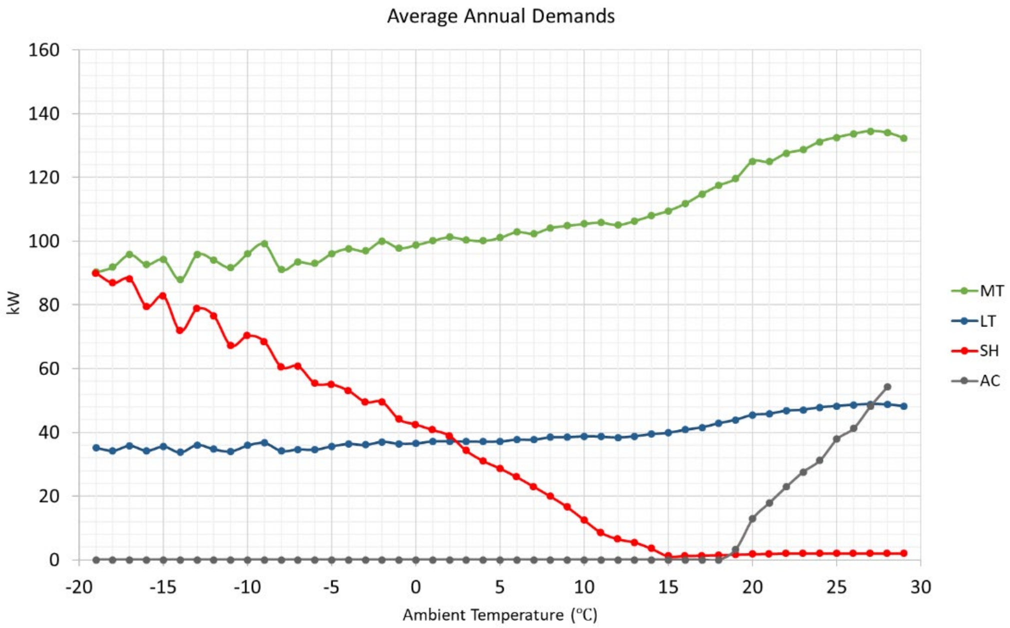

Figure 10: Refrigeration, space heating, and air conditioning demands (in kW) at different outdoor temperatures.

The electric power consumption to cover the thermal demands in Figure 10 were separated using field measurements data analysis combined with computer modelling to simulate the system performance in different operating modes. Coefficient of performance (COP) for each of the system functions was calculated and plotted in Figure 11.

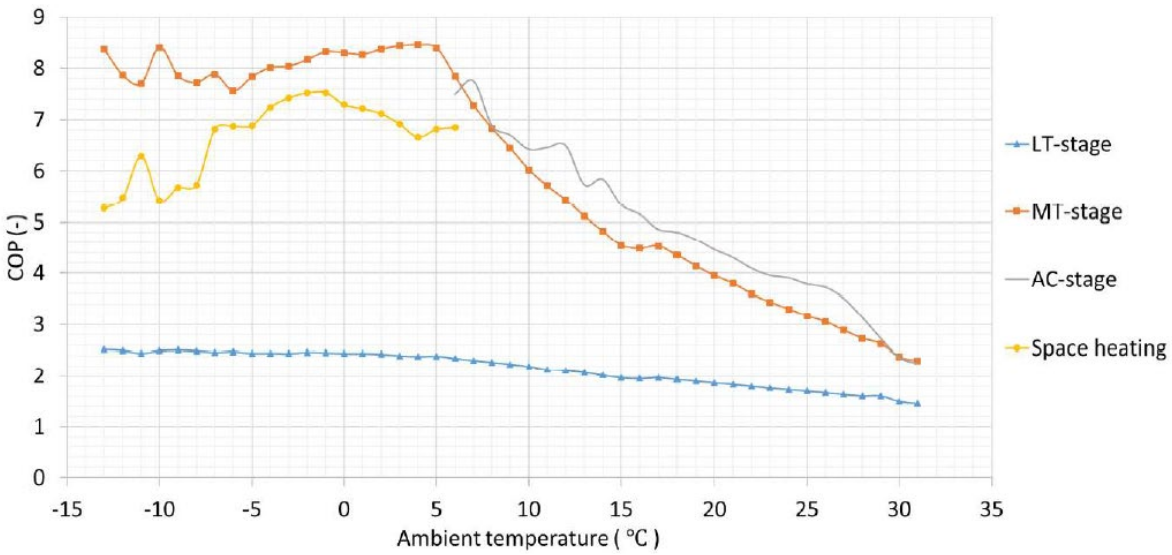

Figure 11: COP_{MT}, COP_{LT}, COP_{AC}, and $COP_{space\ heating}$ (or COP_{HR}) at different outdoor temperatures.

COP_{MT} and COP_{LT} results in Figure 11 agree with earlier studies which show that the CO2 refrigeration system is the most efficient in Swedish climate conditions compared to other alternatives. As can be observed in the figure, COP_{MT} has the highest values, around 8, at outdoor temperatures lower than 5°C, lower than which, the system operates at the minimum condensing temperature of 10°C. COP_{LT} is typically low in such systems due to the low evaporation temperature, around -30°C.

COP_{AC} values are comparable to COP_{MT} because air conditioning function of the system operates at the same evaporation temperature in the MT cabinets. Evaporation temperature in MT cabinets in typical supermarket refrigeration systems does not exceed -10°C, which is low for air conditioning and reduces the efficiency. However, in this system with overfed evaporators the evaporation temperature is expected to higher than typical systems, around -4°C.

Space heating is covered by the refrigeration system at rather high COP, as can be observed in COP_{HR} plot in Figure 11. However, auxiliary electric heater is not included in the calculation of the COP_{HR}, but it will be included in the seasonal performance factor (SPF) calculation in the heat recovery performance section.

Relevant publication/s:

- S. Thanasoulas, J. Arias och S. Sawalha, ”Theoretical analysis of the power and annual energy demands of a supermarket with a CO2 refrigeration cycle,” i 14th Gustav Lorentzen Conference, Kyoto, Japan, 2020.
- S. Thanasoulas, J. Airas och S. Sawalha, ”Supermarket case study: analysis of refrigeration system with heating, air conditioning and ground storage integration,” i 26th International Congress of Refrigeration, Paris, France, 2023.

2.4. Air conditioning performance

In the discussion with project partners on designing the system for the case study, the plan was to include the feature of parallel compressor, which is included in the reference system schematic in Figure 1. Using the parallel compression allows operating the evaporator for air conditioning at higher temperature than what the MT cabinets require, which increases the COP_{AC}. However, at the design phase of the system there has been a discussion on patent rights on the solution connected to a specific company. Therefore, the decision was made to avoid potential legal conflict and exclude this feature from the implemented system solution. Since the evaporators in MT cabinets are overfed, the evaporation temperature was expected to be higher than what is required in typical refrigeration systems, this will bring the evaporation temperature of MT cabinets closer to what is usually required in air conditioning systems. Therefore, reducing the impact on energy use for not using the parallel compression feature.

The monthly air conditioning demands (or space cooling) for 2021 and 2022 are plotted in Figure 12. The “thermal gains” in the plot is due to malfunctioning 3-way valve in the geothermal brine loop, the valve was not separating the flows well enough (i.e. leaking) resulting in the air conditioning system extracting heat from the ground, i.e. cooling the ground at the same time when the ground should be used as a heat sink. This is the reason for the relatively high air conditioning load provided by the refrigeration system in 2021. The 3-way valve was replaced and the demand on air conditioning decreased in 2022, the thermal gains in 2022 is assumed to be due to heat losses from the surrounding to the brine loop and tank.

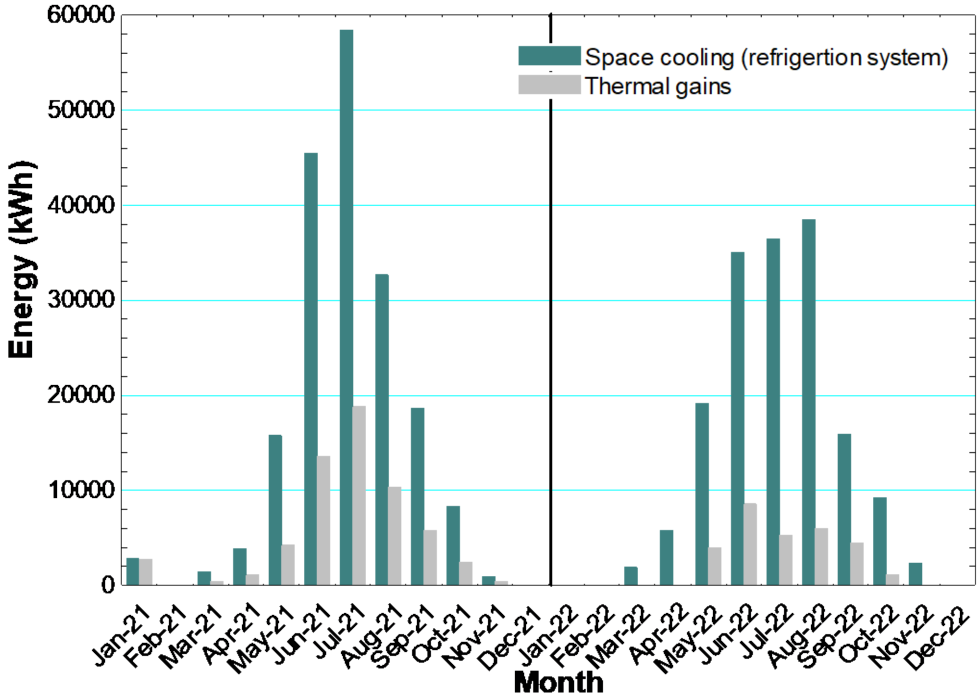

Figure 12: Monthly air conditioning (space cooling) demands for 2021 and 2022.

The Seasonal Energy Efficiency Ratio (SEER) of the air conditioning function of the system is presented in Figure 13. The key factors that influence the SEER, such as, ground sub-cooling, free cooling from the ground, and heat gains, are investigated and presented in Figure 13.

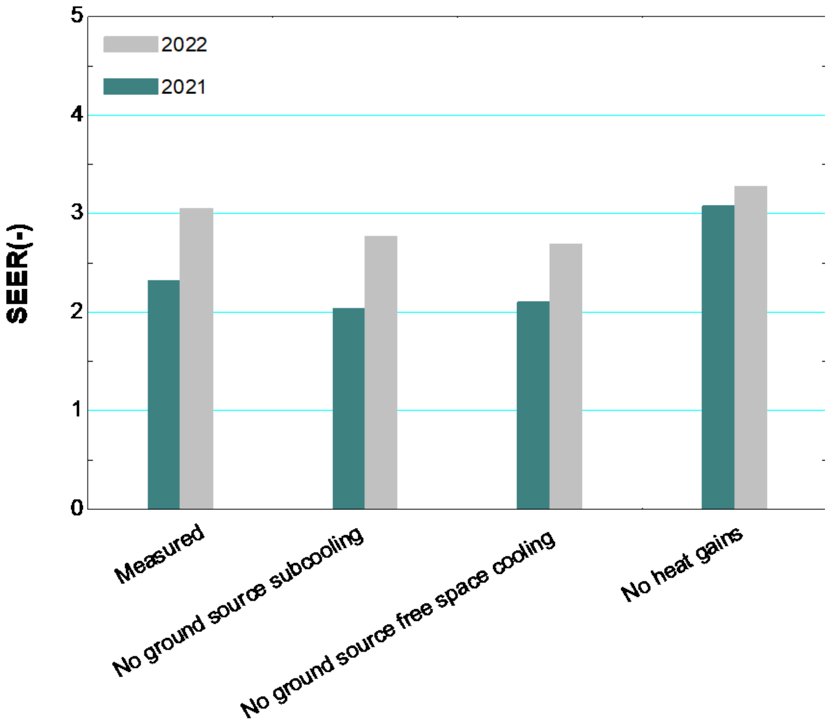

Figure 13: Seasonal Energy Efficiency Ratio (SEER) of the air conditioning function of the system.

As can be observed in Figure 13, air conditioning is provided by the system at SEER of about 3 in 2022. If the system would have had parallel compression operating at higher evaporation temperature than MT cabinets, SEER of around 4 can be expected, similar to the reference system's values presented in Figure 3.

Relevant publication/s:

- S. Thanasoulas, J. Arias och S. Sawalha, "Theoretical analysis of the power and annual energy demands of a supermarket with a CO2 refrigeration cycle," i 14th Gustav Lorentzen Conference, Kyoto, Japan, 2020.
- S. Thanasoulas, J. Airas och S. Sawalha, "Supermarket case study: analysis of refrigeration system with heating, air conditioning and ground storage integration," i 26th International Congress of Refrigeration, Paris, France, 2023.
- C. Perea Díaz, "Field measurement analysis of two supermarkets with advanced energy systems installed in Sweden," MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.

2.5. Heating performance

All heating needs in the supermarket building should be covered by the heat recovered from the refrigeration system. The system is designed to extract heat from the ground when the refrigeration load is not high enough to cover the heating demand. In addition, auxiliary electric heaters can top up the heating capacity of the system at peak heating demand conditions.

The monthly heating demand and the part of the energy system that covers the demand are plotted in Figure 14. The average monthly outdoor temperatures are also plotted, and the SPF is indicated on the plot.

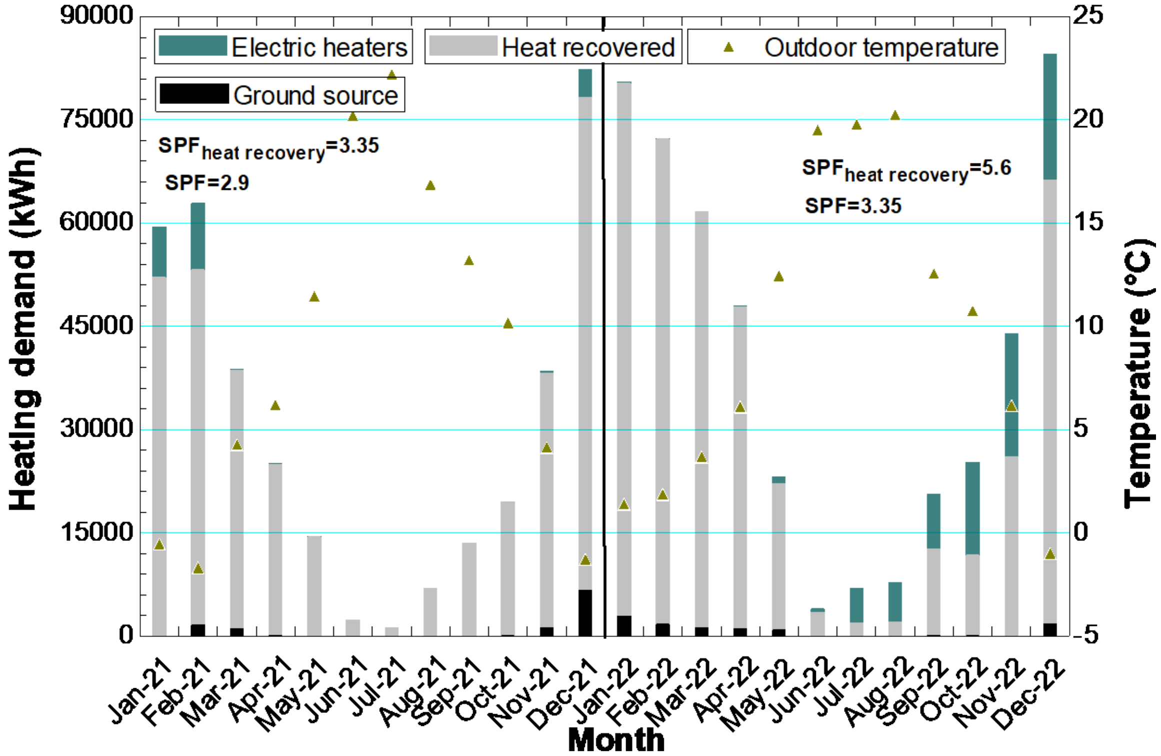

Figure 14: Monthly heating demand and the part of the energy system that covers the demand, average monthly outdoor temperature, and SPF.

In the early months of operation since January 2021, it was observed that the system required adjustments in the control of the heat recovery, so it can run at the optimum conditions. For instant, the discharge pressure was put at a fixed value of about 85bars, which optimally should be regulated to match the heating demand, and the gas cooler was still rejecting considerable amount of heat when it should be running at low capacity to maximize heat recovery capacity. This resulted in the need for electric heaters to cover part of the heating demand. Additionally, no heat was extracted from the ground.

In the following heating season 2021-2022, adjustments to the control system have been implemented and the operation of the system was closer to optimum resulting in more heat recovery from the refrigeration system, extracting heat from the ground, and minimum use of the electric heaters. This can be observed in the period from September 2021 to April 2022.

The heat recovery system encountered technical problems where one of the de-superheaters leaked refrigerant to the water in the heating system in the supermarket building. The fracture in the heat exchanger (de-superheater) is most probably caused by thermal stress in the heat exchanger due to frequent opening and closing of the 3-way valve on the refrigerant side. The degraded system performance for heat recover can be observed in Figure 14 during the winter season in the second half of 2022.

Relevant publication/s:

- S. Thanasoulas, J. Arias och S. Sawalha, ”Theoretical analysis of the power and annual energy demands of a supermarket with a CO2 refrigeration cycle,” i 14th Gustav Lorentzen Conference, Kyoto, Japan, 2020.
- S. Thanasoulas, J. Airas och S. Sawalha, ”Supermarket case study: analysis of refrigeration system with heating, air conditioning and ground storage integration,” i 26th International Congress of Refrigeration, Paris, France, 2023.
- C. Perea Díaz, ”Field measurement analysis of two supermarkets with advanced energy systems installed in Sweden,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.

2.1. Analysis of evaporators overfeeding

Overfeeding the MT level evaporators using liquid ejectors is one of the efficiency increasing features of the CO_2 refrigeration systems for supermarkets. Eliminating the need for internal superheat in the system will improve the heat transfer coefficient in the evaporator, which will allow the system to operate at higher evaporation temperature. Typically, refrigeration systems for supermarkets use control strategies where each cabinet’s evaporator maintains a set value of internal superheat, about 7K. This results in evaporation temperature at about -10°C. With evaporating overfeeding, -4°C evaporation temperature is expected to be sufficient to keep the required air temperature in the cabinets.

Monitoring the evaporation temperature in the cabinets, it was observed that at the start of the system operation it has been running near the expected evaporation temperature for few months, as can be observed in Figure 15, which is a plot of the evaporation over the entire period of system operation.

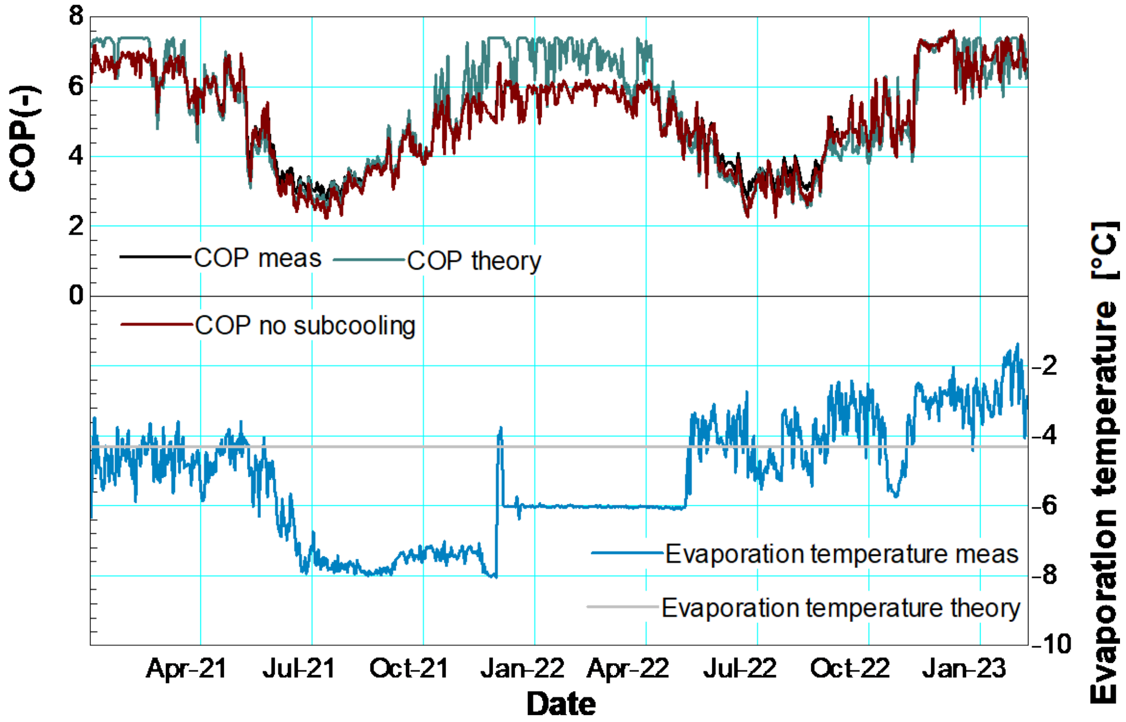

Figure 15: Medium level evaporation temperature and COP_{MT} over the entire period of system operation.

It can be observed in Figure 15 that During May 2021 the settings for some of the cabinets have been changed which resulted in internal superheat in the cabinets and reduced the evaporation temperature of the centralized refrigeration system. After thorough analysis studying the operation of each MT cabinet in the supermarket, the cabinets with the wrong settings that caused the decrease in evaporation temperature have been identified and the settings were changed again in May 2022 to facilitate the overfeeding function. During the last few months of operation, it can be observed that evaporation temperature of around -3°C can be reached.

An example of the analysis that has been performed on the MT cabinets operation can be seen in Figure 16, where the superheat value for each cabinet's evaporator is plotted in a heat map for one day of operation. DK and RK on the left y-axis are the names of the cabinets.

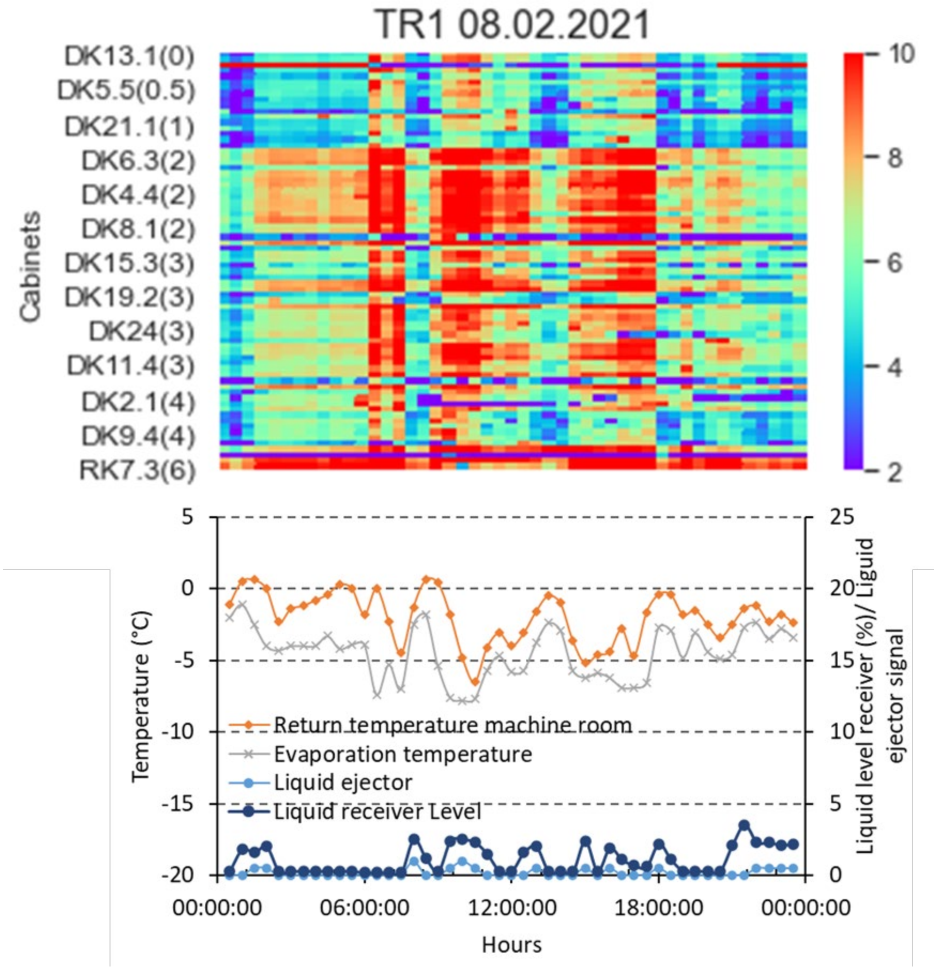

Figure 16: Supermarket cabinets operation for one day (Top) Superheating values of 73 evaporators, right y-axis should read superheat value in Kelvin (Bottom) Hourly average evaporation temperature, return temperature in the machine room, liquid level in the receiver, and liquid ejector signal

The LT cabinets (freezers) were controlled with regular superheat control, which resulted in evaporation temperature of about -30°C, see Figure 17, which is typical evaporation temperature in the freezers in supermarkets.

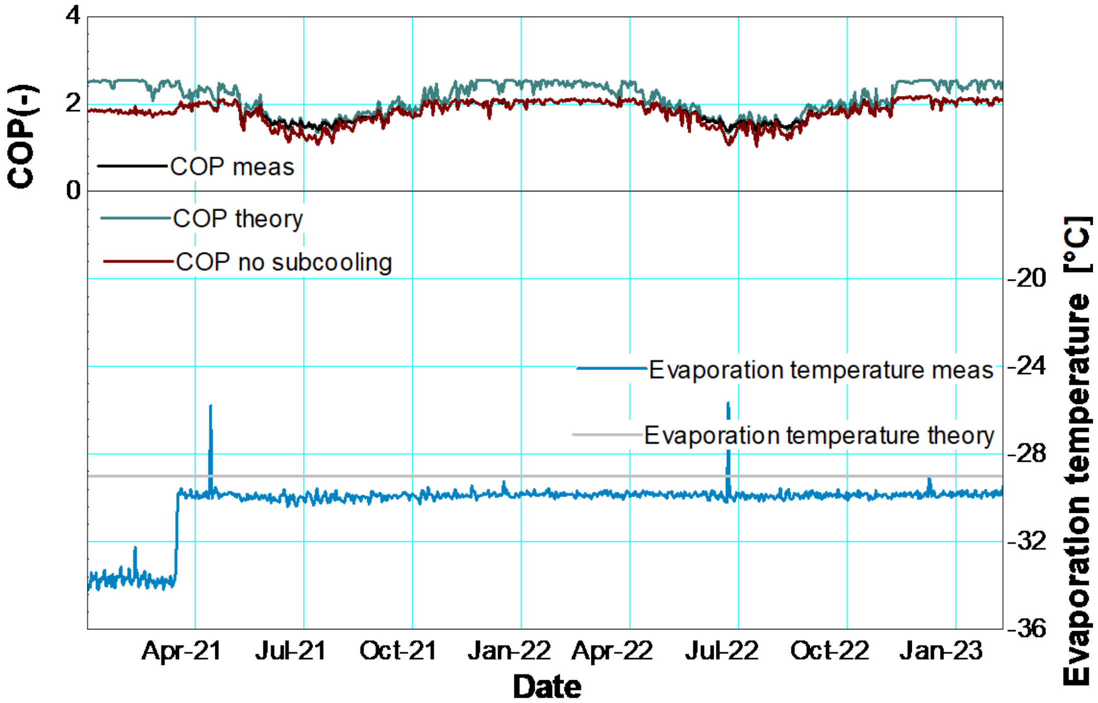

Figure 17: Low level (freezers) evaporation temperature and COP_{LT} over the entire period of system operation.

Overfeeding at LT was not implemented in this system because there is no commercial liquid ejector solution available for LT level and other suggested methods were not tested, therefore, were judged risky to implement.

Relevant publication/s:

- S. Fehling, ”CO2 Refrigeration with Integrated Ejectors: Modelling and Field Data Analysis of Two Ice Rinks and Two Supermarket Systems,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.
- S. Thanasoulas, S. Fehling, J. Arias och S. Sawalha, ”Field measurement analysis of centralized refrigeration systems’ evaporators under overfeed conditions,” i 26th International Congress of Refrigeration, Paris, France, 2023.

2.2. Energy benchmarking

The detailed energy measurements installed in the supermarket in this project facilitated breaking down of the electric power consumption to identify the main electric power consuming activities in the building. The total energy use of the supermarket for 2021 is about 1700 MWh, detailed breakdown of the total energy use is presented in Figure 18.

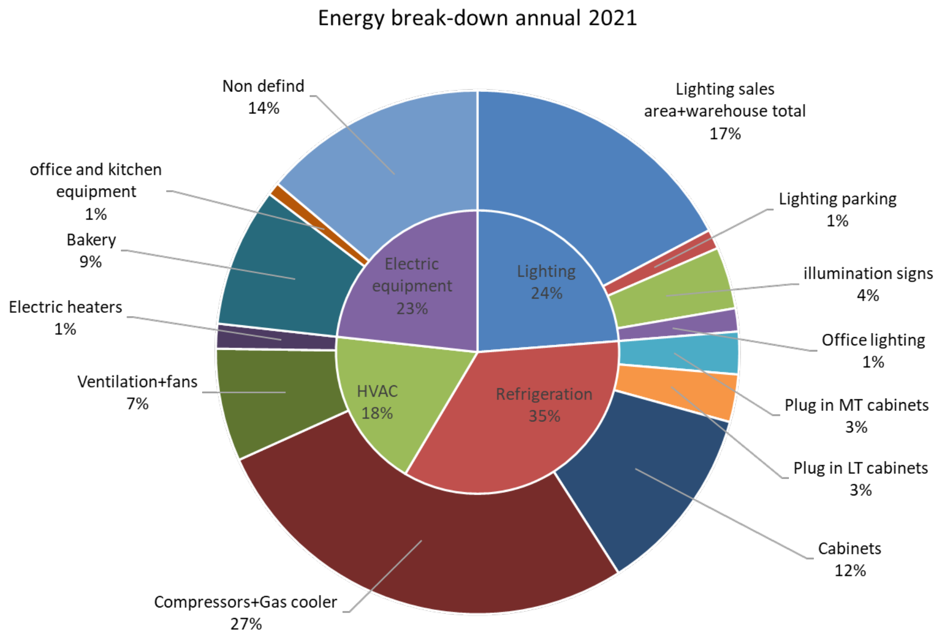

Figure 18: Breakdown of the supermarket's energy use for the year 2021

The refrigeration system in the supermarket is typically responsible for about 50% of the total energy use in the supermarket's building. As can be observed in Figure 18, the refrigeration system accounts for about 35% of the total energy use. This can be a result of a highly efficient refrigeration system or a supermarket that has relatively large energy use in other activities. Therefore, the total energy use of the supermarket has been benchmarked with other supermarkets from earlier studies and new supermarkets data analysed in this project.

There are several key performance indicators for energy benchmarking in supermarkets [2] and [3]. The most common is the annual energy use per square meter of the total area (kWh/year/m^2), for Bålsta supermarket this is about 264 (kWh/year/m^2). Compared to supermarkets from earlier studies including Sweden [3] [2], Bålsta supermarket consumes the least energy in its size category. This can be observed in Figure 19, which is a plot of the annual energy use per square meter of the total area versus total area for supermarkets in Sweden, USA, and Canada.

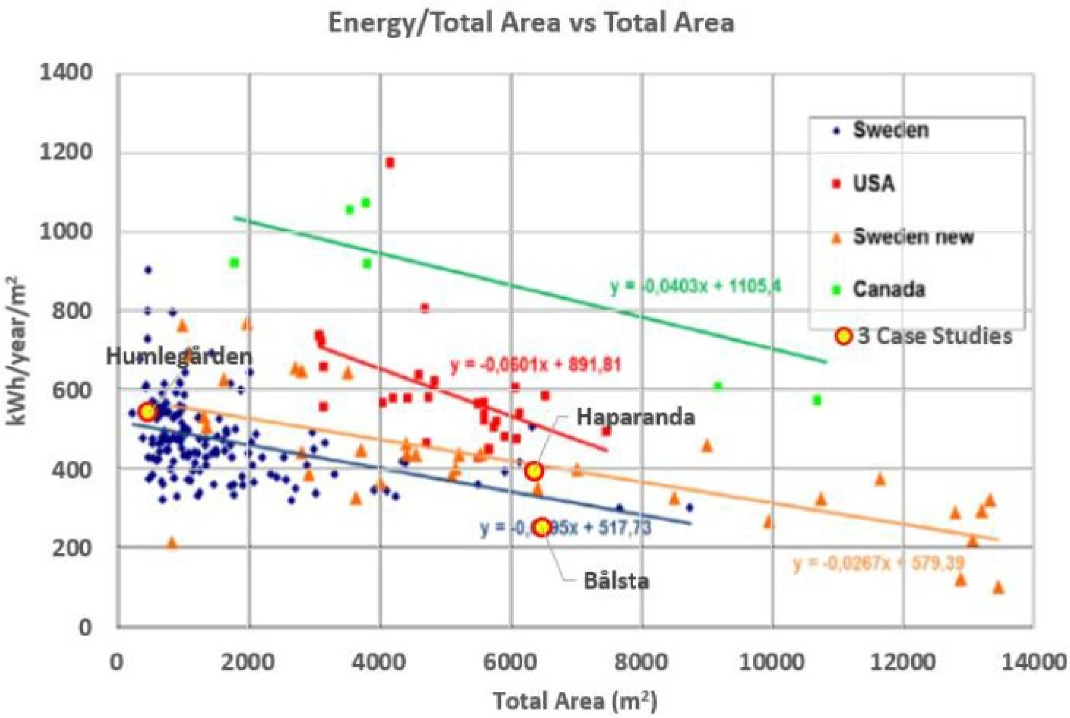

Figure 19: Annual energy use per square meter of the total area versus total area-old data.

The data for Sweden in Figure 19 is for 160 Swedish supermarkets, most of the data are more than 25 years old. Therefore, it was essential to obtain data for newer supermarkets and generate more recent values for the key performance indicators. Data of 29 supermarkets from years 2020 to 2022 was obtained from one of our project partners and curve fitted in Figure 20. Data from the old Swedish supermarkets in Figure 19 was also curve fitted.

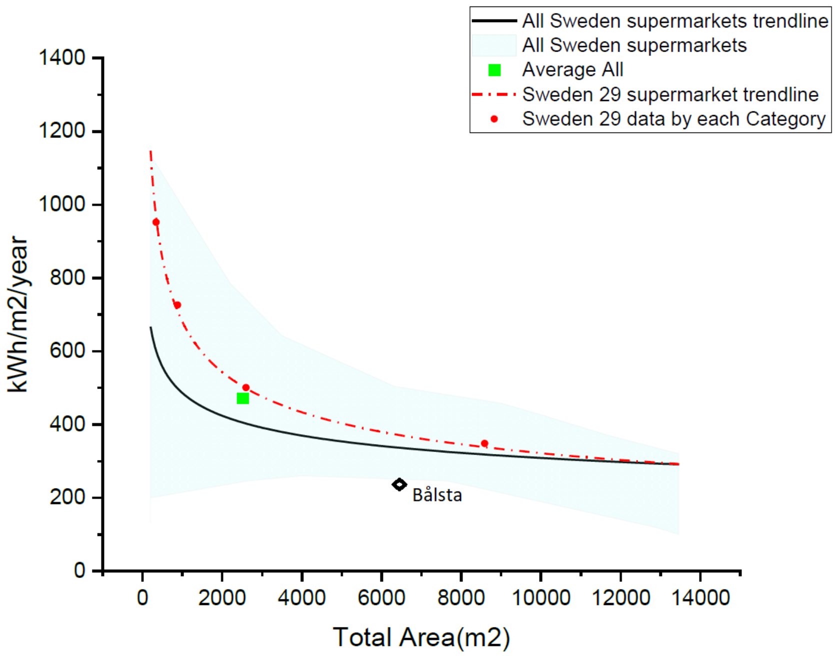

Figure 20: Curve fitting of annual energy use per square meter of the total area versus total area-old data and new data.

As can be observed in the plot in Figure 20, Bålsta supermarket is the least energy consuming among the available old and new supermarket data.

Relevant publication/s:

- S. Shaghiasl, ”Improved Energy Benchmarking of Supermarkets Buildings,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2023.
- A. M. Sreekandath, ”Analysis of Energy Performance Indicators for Supermarket Buildings,” MSc thesis, Energy Technology department, KTH, Stockholm Sweden, 2021.

2.3. Evaluation of Building modelling

Building efficient energy systems for supermarkets starts from the design phase where good estimation of the thermal demands is essential to select the matching system and component capacities. This will ensure that that thermal demands are always covered, and the system is not over sized, therefore, the energy bill and the installation cost of the system is kept to minimum.

An accurate building simulation calculation tool can also be used to follow the system performance and detect noticeable deviations from the simulation results. For example, in Bålsta supermarket the air conditioning load from the field measurements was much higher than estimated by the building model, which lead to investigation that detected a faulty 3-way valve on the geothermal brine loop resulted in the system cooling the ground, adding unnecessary load on the system.

Energy benchmarking of supermarkets buildings require verified energy data and building information for large number of supermarkets. The data and building information are difficult to collect and require time consuming processing before it can be used for benchmarking. A validated energy simulation model of supermarket buildings can be powerful tool to generate data for energy benchmarking, reducing the need for large amount of data collection and processing.

Two building simulation tools have investigated in this project and compared to the real data from Bålsta supermarket. EnergyPlus [4] is an open-source software used in energy analysis at design stage. This tool can be used to model a supermarkets' refrigeration system and accounting for the sensible and latent heat exchanges between the refrigerated cases and the HVAC system.

CyberMart is a building simulation tool created in the Energy Technology department at KTH. It is designed specifically to simulate the energy demand of supermarket buildings in accordance with the required set points and store's characteristics [5].

The thermal demands for refrigeration, heating, air conditioning (cooling) are calculated in EnergyPlus and CyberMart and compared to the results from Bålsta. The results are presented in Figure 21.

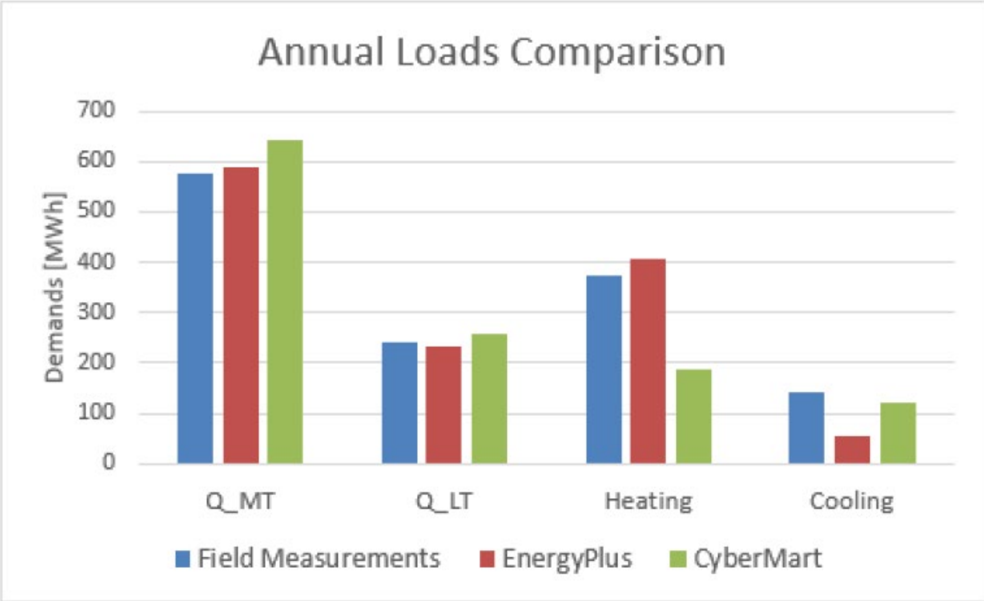

Figure 21: Thermal demands comparison: Field Measurements, EnergyPlus, and CyberMart's for the year 2021.

As can be observed in Figure 21, EnergyPlus' model results are closer to the measurements of refrigeration and heating loads than CyberMart, however, EnergyPlus simulation results deviates from measurements for air conditioning load, which can be attributed to the unnecessary additional load on air conditioning caused by the faulty 3-way valve.

The electric energy use to cover the thermal demands is calculated using the modelling tools and presented in Figure 22, together with the energy use by the different subsystems. The total electric energy use of the supermarket during 2021 is calculated and presented in Figure 23. In both figures the measurements from Bålsta are also included.

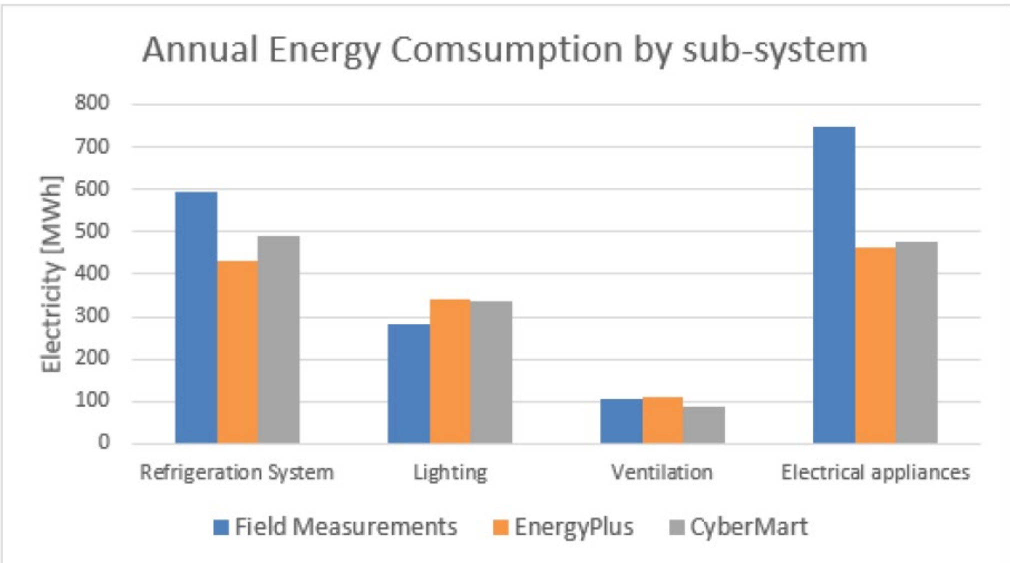

Figure 22: Annual energy use by the refrigeration system and other sub-systems according to the field measurements, EnergyPlus, and CyberMart's for year 2021.

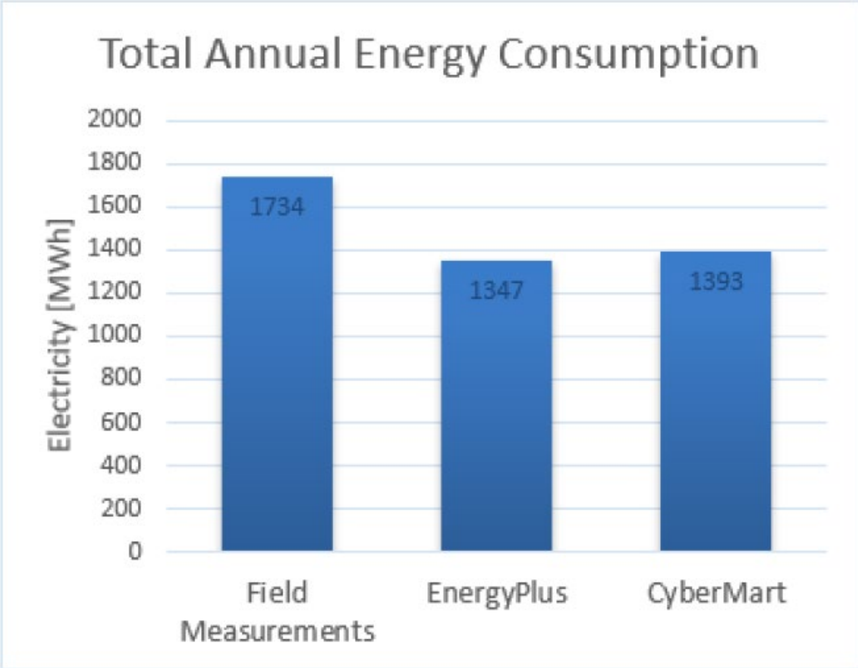

Figure 23: Annual energy use of the supermarket according to the field measurements, EnergyPlus, and CyberMart's for the year 2021.

As can be observed in Figure 23, EnergyPlus' model predicts a 22% lower annual consumption, whereas CyberMart's value is 20% lower than the measured total annual consumption. CyberMart's model resulted in a closer value to the field measurements, even though EnergyPlus' thermal loads were more accurate.

Large difference between the modelling tools and the field measurements results can be observed in the "Electrical appliances" category in Figure 22. This category includes activities in pharmacy, bakery, offices, and storage rooms (not refrigeration), where assumptions with high level of uncertainties are made.

Most of the results from CyberMart tool were close to the EnergyPlus, however, CyberMart was found to be much more user-friendly. The energy category that needs further calibration in both tools has been identified, such as the heating demand in CyberMart, the energy use of the refrigeration system and the electrical appliances in both tools. However, the electrical appliances category maybe calculated well in the simulation tools, but requires more accurate inputs to the models.

Relevant publication/s:

- B. Corceiro, "Energy Efficiency Assessment, based on Field Measurements and Computational Simulations: A Swedish Hypermarket's case study," MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2022.

2.4. Additional case studies

At the project start and during the discussion with industrial partners on selecting the case study, it was decided to investigate additional supermarkets as supporting case studies with common features to the reference case study of Bålsta supermarket. The supporting case studies had some other interesting features that were not possible to implement in Bålsta and were defined as good examples.

Working with the supporting case studies, it was possible to test our simulation models results on the field data of already existing systems before Bålsta supermarket was in operation, also it was possible to get insight into the expected challenges when dealing with system performance analysis and system control. The supporting case studies were already in operation at the project start and they have been investigated in parallel to the selection and design process of Bålsta supermarket.

2.4.1. Moraberg supermarket

Key features of the energy system in the supermarket are the liquid ejector overfeeding for MT cabinets and the parallel compression for air conditioning. The parallel compression is a missing feature from Bålsta supermarket due to patent claims.

Comprehensive analysis of the energy system of the supermarket was conducted in two master thesis projects [6] [7]. However, only sample of the results will be discussed in this section. The overfeeding function was studied for all the cabinets in the supermarket, which showed that the system was not running with low superheat at the start of the investigations, but after increasing the air temperature setpoint for the cabinets, the superheat was decreased due to accomplishing overfeeding in most of the cabinets. The difference in evaporation temperature between the operation in August and November 2020 can be observed in one of the MT cabinet's temperature plots in Figure 24.

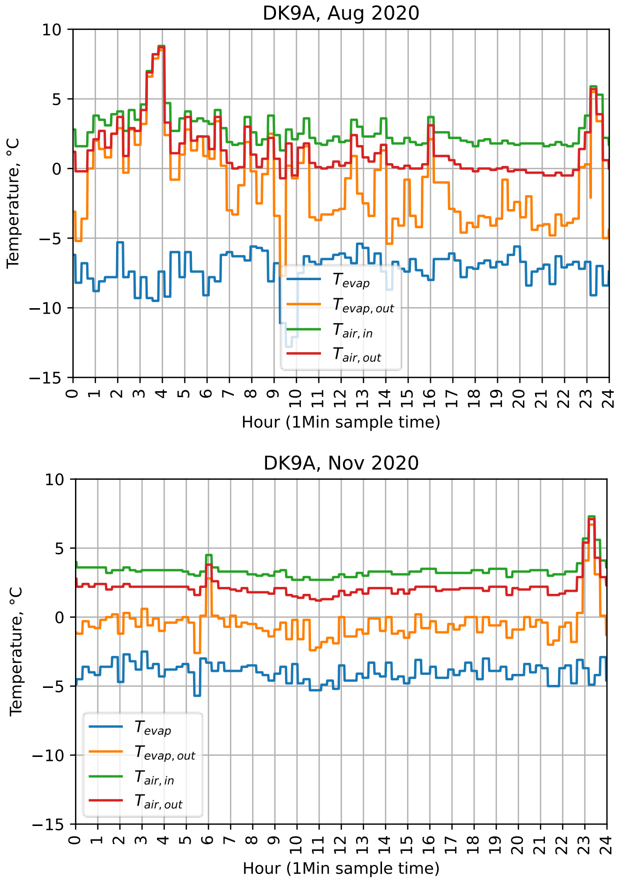

Figure 24: Selected cabinet temperature plots for one day in August and one day in November 2020.

The analysis of air conditioning function in Moraberg supermarket showed the potential for achieving high COP_{AC} with parallel compression, this can be observed in the high SEER value presented in Figure 25. However, this effect is not only due to parallel compression, but also due the efficient use of free cooling from the ground.

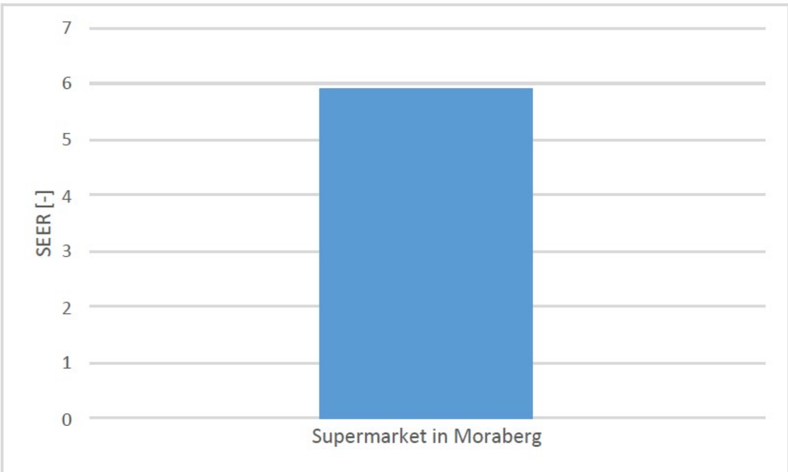

Figure 25: Seasonal Energy Efficiency Ratio (SEER) for AC in Moraberg (REF).

Relevant publication/s:

- S. Fehling, ”CO2 Refrigeration with Integrated Ejectors: Modelling and Field Data Analysis of Two Ice Rinks and Two Supermarket Systems,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.
- C. Perea Díaz, ”Field measurement analysis of two supermarkets with advanced energy systems installed in Sweden,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.

2.4.2. Stenhagen supermarket

Stenhagen supermarket is a special case study where its energy system exports all heating and air conditioning demands to neighbouring building, see the illustration schematic in Figure 26. The investigations in this study focused on studying the potential of utilizing the efficient heat recovery and air conditioning functions of the refrigeration system to export heat and air conditioning to neighbouring buildings, techno-economic analysis was also conducted.

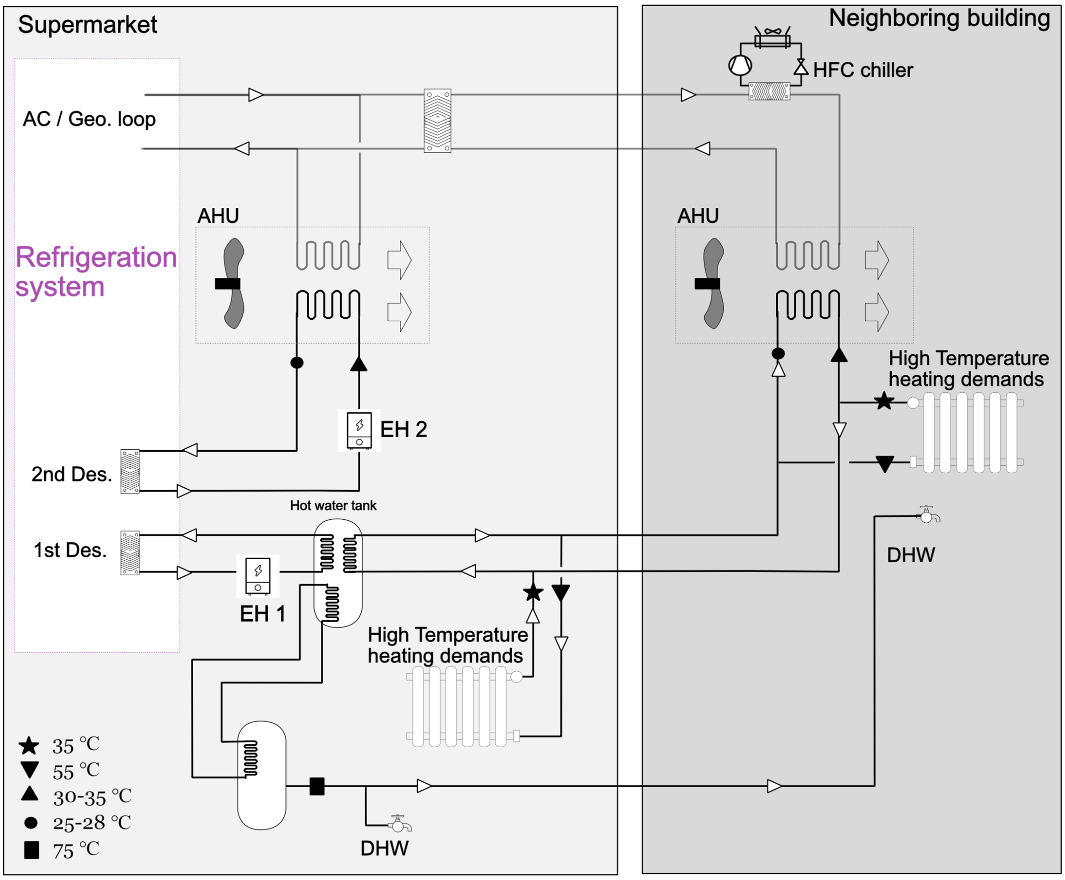

Figure 26: Schematic of Stenhagen’s energy system including heating, AC, AHU, and auxiliary heating.

Figure 27 and Figure 28 show, based on field measurements analysis, the amount of air conditioning and heat provided by the refrigeration system to the supermarket and neighbouring buildings. The capacity for providing heating in the system is increased by the installed 20 boreholes with 225m depth each.

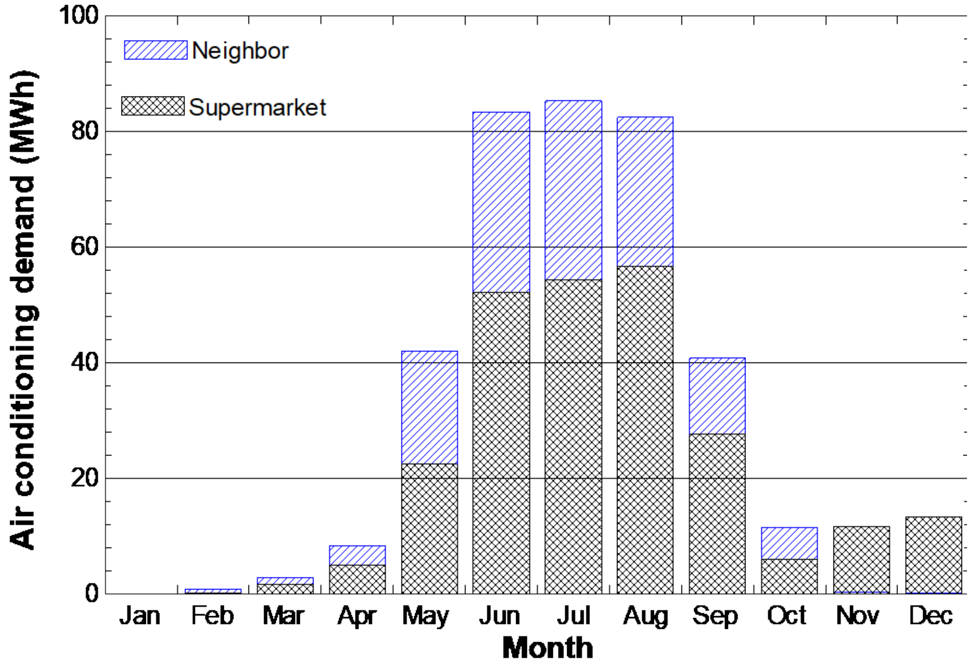

Figure 27: Monthly air conditioning demands breakdown for supermarket and neighbouring building for year 2019.

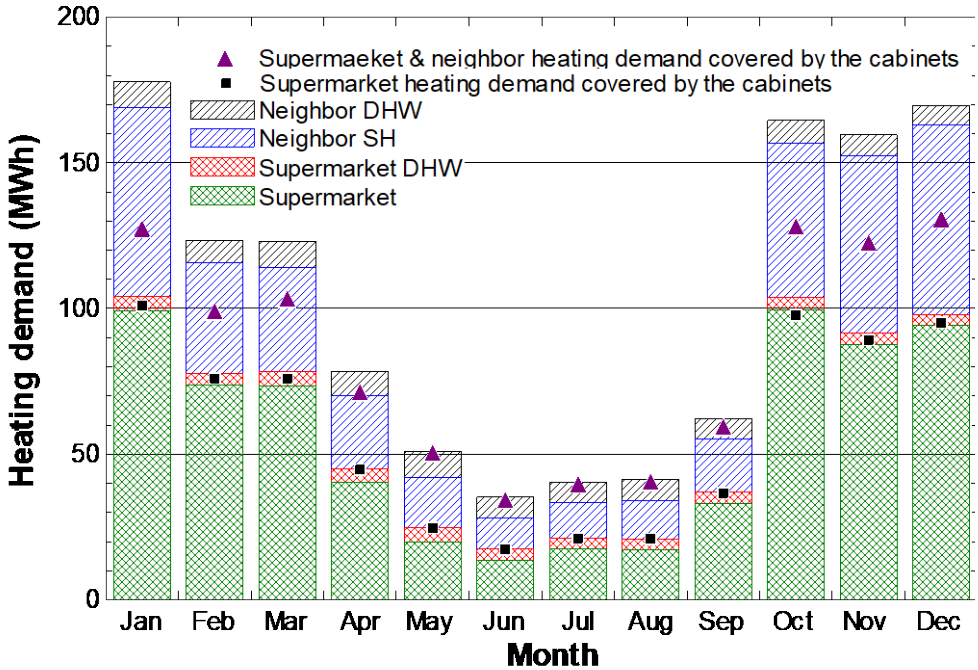

Figure 28: Monthly heating demands breakdown for supermarket and neighbouring building for year 2019.

The efficiency of the system for heat recovery is reflected in the price of the generated heat, which is compared to the typical price for district heating, as can be observed in Figure 29.

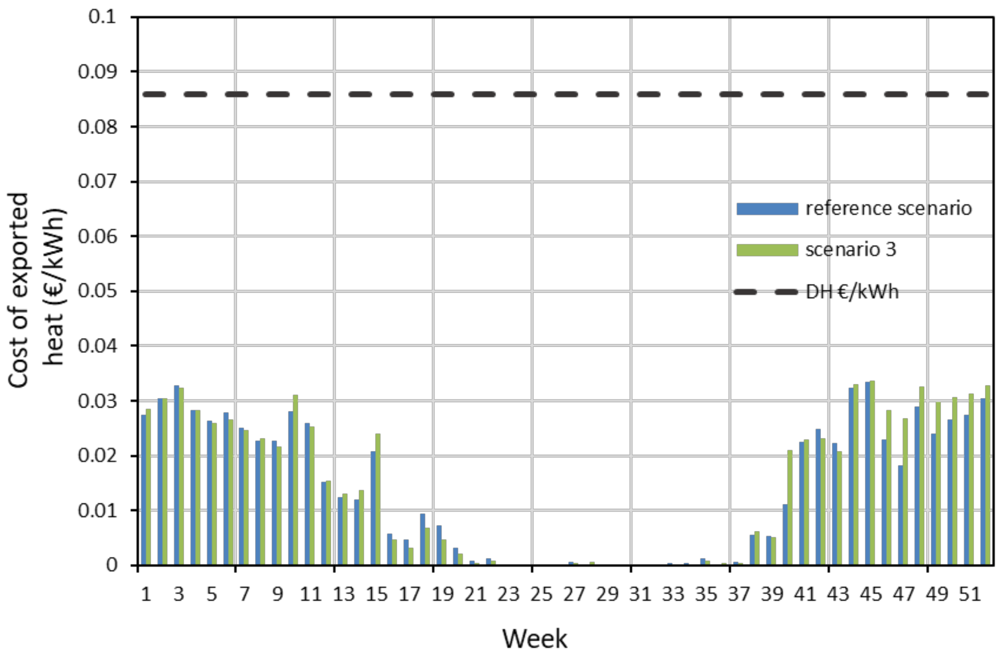

Figure 29: Cost of heat provided to the neighbouring building compared to price of district heating. Price of electricity is assumed 0.1 €/kWh

The results show that the neighbouring building has 67% annual operating cost savings when its thermal demands are covered by the supermarket, this is in comparison to a typical solution in large cities in Sweden where the heat is bought from district heating and cooling networks. The supermarket's refrigeration cabinets are the heat source that cover 80% of the total heat demand, while the ground heat source covers the remaining 20%.

Relevant publication/s:

- C. Perea Díaz, ”Field measurement analysis of two supermarkets with advanced energy systems installed in Sweden,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.
- S. Thanasoulas, J. Arias och S. Sawalha, ”Investigating the heating and air conditioning provision capability of a supermarket to neighboring buildings: Field measurement analysis and economic evaluation,” Applied Thermal Engineering, Vol. %1 av %2230, Part B, nr 1359-4311, p. 120782, 2023.

Energimyndigheten

3. Discussion

This project applied the knowledge accumulated through the research in supermarket energy systems by building a unique case study, where today's most efficient, environmentally friendly and cost-effective features of an energy system for supermarkets were implemented. A highly efficient supermarket was designed, installed, monitored, thoroughly evaluated, and well documented.

The energy system implemented in the supermarket case study is an integrated energy system providing all thermal demands in the supermarket building. Therefore, it was essential to study the separate functions of the system and compare the performance to other standalone alternatives. The overall system performance was also studied and compared to other supermarkets data in Sweden.

The system provided refrigeration at the expected high COP from CO2 refrigeration system were overfeeding the medium temperature evaporators using the ejector resulted in operating the system at high evaporation temperature, up to around -3°C. The energy saving benefits from overfeeding the evaporators were compromised when supermarket personnel changed the settings of the cabinets, which was observed from the field measurement data. It was noticed that wrong temperature settings of a single cabinet would trigger the centralized refrigeration system to operate at low evaporation temperature and reduce the system's efficiency. In this case study, the system was closely monitored, and active communication was kept with the relevant project partners to make the necessary adjustments in the system to set it back to good operating conditions. However, in typical procedures the system could be equipped with liquid ejector, but still running at unfavourable conditions for energy efficiency without being detected. Good operating procedures and smart monitoring are essential to guarantee that the systems are running at the favourable conditions for energy efficiency.

The system provided air conditioning with SEER of about 3, but there is a potential for the system to provide air condition at higher efficiency if parallel compression would have been implemented. This can be observed when comparing the results of the case study to the supermarket in Moraberg, where parallel compression is implemented and the geothermal system was used efficiently, providing fee cooling when possible. Air conditioning in Moraberg's system was provided at SEER close to 6.

The heat recovery function of the system required adjustments to run as close as possible at the optimum conditions, which resulted in high SPF of about 6. After a season of good run, the heat exchanger extracting heat from the refrigeration system to the buildings heating system was fractured and leaked CO2 into the building's heating system loop, which resulted in large scale maintenance task. The problem in the heat exchanger was attributed to thermal stress due to the frequent opening and closing of the 3-way valve. Discussion has been taking place among relevant partners to verify the cause and suggest a solution for this technical problem. Possible solutions can be an improved design of the heat exchanger or a control strategy where conditions that lead to thermal stress can be avoided.

The overall energy use of the system was analysed by benchmarking it with other supermarkets. Bålsta supermarket building had about 264 (kWh/year/m2), which is much lower than other supermarkets from earlier studies including Sweden. Bålsta supermarket consumes the least energy in its size category, according to the available supermarket data. However, most of the supermarket data used in the energy benchmarking is very old, from more than 25 years ago. Newer data are limited, and if available it requires large amount of processing and verification before they can be used for benchmarking. Despite the importance of energy benchmarking and the efforts over the years, today there is no reliable or up-to-date benchmarking for supermarket buildings. Proper benchmarking requires good quality data collection and information gathering on each supermarket in an extensive database, this is a major task that requires several actors to work together.

Two building simulation tools, EnergyPlus and CyberMart, have investigated in this project and compared to the real data from Bålsta supermarket. The tools predicted reasonably well the thermal demands, with closer results from EnergPlus to the field measurements. The tools are reasonably accurate to generate the thermal loads for designing a supermarket system. Which is essential to select the matching system and component capacities. This will ensure that that thermal demands are always covered, and the system is not over sized, therefore, the energy bill and the installation cost of the system is kept to minimum.

However, both tools underestimated the energy use for the refrigeration system and the electrical appliances. It is important to validate and calibrate the building modelling tools which then can be used for energy benchmarking. As discussed in the energy benchmarking part in this project, benchmarking of supermarkets buildings requires verified energy data and building information for large number of supermarkets. The data and building information are difficult to collect and require time consuming processing before it can be used for benchmarking. A validated energy simulation model of supermarket buildings can be powerful tool to generate data for energy benchmarking, reducing the need for large amount of data collection and processing.

An accurate building simulation calculation tool can also be used to follow the system performance and detect noticeable deviations from the simulation results. For example, in Bålsta supermarket the air conditioning load from the field measurements was much higher than estimated by the building model, which lead to investigation that detected a faulty 3-way valve on the geothermal brine loop resulted in the system cooling the ground, adding unnecessary load on the system.

The supporting case studies of Moraberg and Stenhagen supermarkets, provided valuable information on the possibilities and potentials of full utilization of some of the energy efficiency features that has been missing or not possible to implement in Bålsta. This is important resource of information for building the future supermarket energy systems.

4. Publication list

Journal papers

1. S. Thanasoulas, J. Arias och S. Sawalha, ”Investigating the heating and air conditioning provision capability of a supermarket to neighboring buildings: Field measurement analysis and economic evaluation,” Applied Thermal Engineering, Vol. %1 av %2230, Part B, nr 1359-4311, p. 120782, 2023.
2. Draft paper with preliminary title: Comprehensive Analysis of Energy Consumption in Supermarkets: Field Measurement, Theoretical Modeling, and Parametric Evaluation

Conference papers:

1. S. Thanasoulas, C. Perea Diaz och S. Sawalha, ”Field measurement analysis of integrated refrigeration system in a new supermarket,” i 14th Gustav Lorentzen Conference, Kyoto, 2020.
2. S. Thanasoulas, J. Arias och S. Sawalha, ”Theoretical analysis of the power and annual energy demands of a supermarket with a CO2 refrigeration cycle,” i 14th Gustav Lorentzen Conference, Kyoto, Japan, 2020.
3. S. Thanasoulas, S. Fehling, J. Arias och S. Sawalha, ”Field measurement analysis of centralized refrigeration systems’ evaporators under overfeed conditions,” i 26th International Congress of Refrigeration, Paris, France, 2023.
4. S. Thanasoulas, J. Airas och S. Sawalha, ”Supermarket case study: analysis of refrigeration system with heating, air conditioning and ground storage integration,” i 26th International Congress of Refrigeration, Paris, France, 2023.

Local magazines

1. S. Sawalha. Bra styrning och koldioxid ger en energieffektiv i butik, Energi&Miljö, October, 2018.

MSc thesis reports

1. B. Corceiro, ”Energy Efficiency Assessment,based on Field Measurements and Computational Simulations: A Swedish Hypermarket’s case study,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2022.
2. S. Fehling, ”CO2 Refrigeration with Integrated Ejectors: Modelling and Field Data Analysis of Two Ice Rinks and Two Supermarket Systems,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.
3. C. Perea Díaz, ”Field measurement analysis of two supermarkets with advanced energy systems installed in Sweden,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.
4. S. Shaghiasl, ”Improved Energy Benchmarking of Supermarkets Buildings,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2023.

5. M. Sreekandath, ”Analysis of Energy Performance Indicators for Supermarket Buildings,” MSc thesis, Energy Technology department, KTH, Stockholm Sweden, 2021.

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5. References

[1] M. Karampour, ”State-of-the-art Integrated Refrigeration Systems in Supermarkets: An Energy Efficiency Evaluation Based on Field Measurements Analysis and Computer Simulations, Doctoral thesis,” KTH, Stockholm, 2021.

[2] IEA, ”Annex 44 HPT IEA-Performance indicators for energy efficient supermarket buildings,” IEA Heat Pump Centre, 2017.

[3] IEA, ”Annex 31 HPT IEA- Advanced Modeling and Tools for Analysis of Energy Use in Supermarkets,” IEA Heat Pump Centre, 2012.

[4] EnergyPlus, ” US department of Energy,” 03 July 2024. [Online]. Available: https://energyplus.net/. [Använd 03 July 2024].

[5] J. Arias, ”Energy Usage in Supermarkets - Modelling and Field Measurements,” KTH, Stockholm, 2005.

[6] S. Fehling, ”CO2 Refrigeration with Integrated Ejectors: Modelling and Field Data Analysis of Two Ice Rinks and Two Supermarket Systems,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.

[7] C. Perea Díaz, ”Field measurement analysis of two supermarkets with advanced energy systems installed in Sweden,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2021.

[8] S. Thanasoulas, J. Arias och S. Sawalha, ”Theoretical analysis of the power and annual energy demands of a supermarket with a CO2 refrigeration cycle,” i *14th Gustav Lorentzen Conference*, Kyoto, Japan, 2020.

[9] S. Thanasoulas, C. Perea Diaz och S. Sawalha, ”Field measurement analysis of integrated refrigeration system in a new supermarket,” i *14th Gustav Lorentzen Conference*, Kyoto, Japan, 2020.

[10] S. Thanasoulas, J. Airas och S. Sawalha, ”Supermarket case study: analysis of refrigeration system with heating, air conditioning and ground storage integration,” i *26th International Congress of Refrigeration*, Paris, France, 2023.

[11] S. Thanasoulas, S. Fehling, J. Arias och S. Sawalha, ”Field measurement analysis of centralized refrigeration systems’ evaporators under overfeed conditions,” i *26th International Congress of Refrigeration*, Paris, France, 2023.

[12] B. Corceiro, ”Energy Efficiency Assessment,based on Field Measurements and Computational Simulations: A Swedish Hypermarket’s case study,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2022.

[13] S. Shaghiasl, ”Improved Energy Benchmarking of Supermarkets Buildings,” MSc thesis, Energy Technology department, KTH, Stockholm, Sweden, 2023.

[14] A. M. Sreekandath, ”Analysis of Energy Performance Indicators for Supermarket Buildings,” MSc thesis, Energy Technology department, KTH, Stockholm Sweden, 2021.